PHYSICAL AND CHEMICAL ENVIRONMENT OF THE GAMBIA RIVER, WEST AFRICA 1983-1984

by

Thomas D. Berry, Russell A. Moll, Gerald L. Krausse

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INTRODUCTION

In comparison to North American and European rivers, studies of tropical rivers are relatively sparse. As a result, seasonal cycles of important elements and annual loads of critical nutrients are far from being understood. Preliminary investigations have shown unexpected large annual ranges in many of the chemical characteristics of tropical rivers (Richey et al. 1980, Meybeck 1982). These ranges arise in part because of annual cycles of rainfall; the rapid increase in streamflows associated with the onset of annual rains drastically alters nutrient loads (Lesack et al. 1984). In addition, flooded river banks release large amounts of organic matter which greatly enrich the river water (Welcomme 1979). The overall consensus, from studies of tropical rivers, is that the relatively uniform annual climate of the tropics is not matched by the cycles of soluble and fine particulate material in the rivers (Beadle 1981).

The motivation behind many of the studies of tropical rivers is a desire to develop the freshwater natural resources. Because river basin studies in developing countries have increased in frequency over the past decade, the general base of knowledge concerning tropical rivers is rapidly expanding (Bernacsek 1984). Large rivers, especially those which flow through arid regions, are a resource which can be effective in mitigating such a basic problem as lack of domestic food production. Management of these large resources generally requires a regional approach (usually multiple nation), and often requires a compromise among many users. Even with careful planning, many river basin development programs have either not fully succeeded or left many people worse off than before (George 1972). Prevention of future failures is

more than ample reason for careful study prior to implementation of development programs.

In 1982 The University of Michigan began an extensive and intensive study of the Gambia River Basin through a contract with the United States Agency for International Development. This far-reaching study included research in environmental as well as social sciences. The primary objectives of the overall study were to determine the existing (baseline) conditions within the Gambia River Basin and to project the types and extents of probable impacts to the basin during development. The focal point of the development program is a series of up to five dams along the river. Thus included in the objectives of the study was to develop an understanding of how these dams will ultimately affect the river both during and after construction.

The Gambia River Basin Study (GRBS) was divided into four distinct but related sub-studies: aquatic or river resources, wildlife/vegetation, public health, and socio-economic. The common factor among these sub-studies was the use and management of water in the Gambia River Basin. This report, which originates from the river resources portion of the GRBS, is restricted to the aquatic sciences. It is further restricted in that it deals with only one aspect of the river resources study, the physical and chemical environment. The primary emphasis in the material that follows is a description of the physical-chemical aquatic environment in 1983-84, before river basin development. Similar reports have been written for other disciplines in aquatic sciences, plankton ecology (Healey et al. 1985), invertebrate ecology (van Maren 1985), mangrove ecology (Twilley 1985), and fish ecology (Dorr et al. 1985). An overall synthesis of the results of the river resources study of the Gambia River is also available (Moll et al. 1984).

While many study approaches were available for the river resources study, the chosen method relied heavily on original data collection. The rationale for this approach was twofold. First, that insufficient data existed concerning aquatic resources of the Gambia River for extensive conclusions to be made about probable impacts of river basin development. Second was the desire to move away from drawing conclusions by supposition and toward drawing conclusions by inference. The distinction is that conclusions drawn from supposition are those that arise by examination of related information from outside of the Gambia River Basin. On the other hand, conclusions by inferences are drawn by first collecting original and relevant data from the system under investigation, and then developing conclusions from those data. While conclusions from inference require considerably more effort to develop, they are almost always stronger and more directed toward the main problems being addressed. The results presented below were made almost entirely by inferences.

EXPERIMENTAL DESIGN AND METHODS

EXPERIMENTAL DESIGN

In order to develop a reasonable understanding of the results presented below, some familiarity with the experimental design is required. A brief description of the experimental design is given below, while for more detail the reader is referred to Moll and Dorr (1983).

The dominant concept used in designing the sampling plan was to integrate all parts of the study into a cohesive plan. This meant that the same basic sampling program was used for the physical-chemical variables as for the biological variables. Measurement of both sets of variables together enhances the overall understanding of the ecology of the river. This enhanced understanding was an invaluable factor in prediction of the impacts on the aquatic system from river basin development.

The sampling program relied upon a stratified sampling approach rather than total random sampling. This approach was utilized because on a river system as large and as varied as the Gambia River, in-depth knowledge of the entire system cannot be achieved in a one-year field program. Rather, the river was divided into five distinct ecological zones and sampling was conducted at one key location in each of these five zones. The zones were determined from a review of previous studies of the Gambia River (see Monteillet and Plaziat 1979), and a reconnaissance of the river six months prior to the beginning of field sampling. These zones were designated as lower estuary, upper estuary, lower freshwater river, upper freshwater river, and headwaters. Each zone was defined by a suite of physical and biological variables, and then approximate geographic boundaries were set for each zone. Briefly, the criteria used to define each zone were as follows: lower estuary - high

salinity (from 35 ppt to the maximum intrusion of 30 ppt) with a distinct marine flora and fauna; upper estuary - moderate (less than 30 ppt) to low salinity at some time during the year; lower river - fresh water throughout the year but the river has distinct tidal fluctuations; upper river - primarily a slow moving river with occasional rapids and no tidal fluctuations; headwaters - predominantly streams with rapids and pools flowing through hilly or mountainous terrain. Geographically the upstream boundaries of these zones were approximated as follows: lower estuary - Mootah Point; upper estuary - Kuntaur; lower river - Barrakunda Falls; upper river - the Senegal-Guinea border; headwaters - the source near Labe (Fig. 1).

The sampling program used for the river resources study consisted of three distinct sub-programs. These sub-programs were the ecological survey, the mangrove and flood plains study, and process studies. Although each sub-program had its own experimental design, the sampling effort included as much correspondence between sub-programs as possible. The ecological survey constituted more than two thirds of the total sampling program. The results presented below primarily come from the ecological survey.

The main consideration used in determining the experimental design of the ecological survey was that a suite of research hypotheses would be tested to reveal what influence various factors had on the aquatic environment. The major factors considered in the design were spatial heterogeneity and temporal variation. The three sources of spatial heterogeneity were longitudinal (along the river), latitudinal (across the river), and vertical (depth of the water). Temporal variation is the change associated with time at one place. Temporal variation in the estuarine and lower river zones was due to both diel

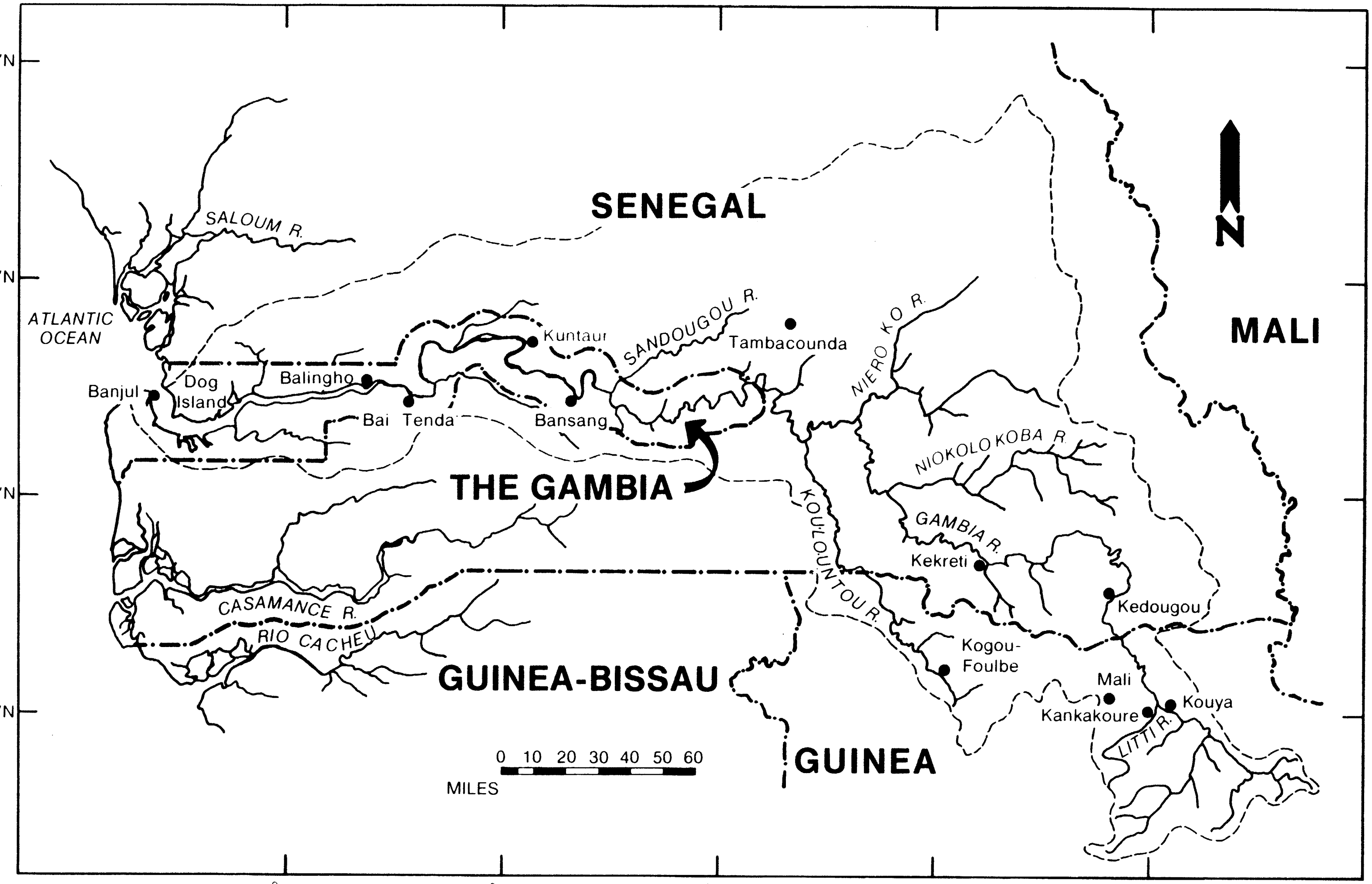

FIGURE 1. Drainage basin of the Gambia River, within dashed lines.

(day-night) and tidal (high water-low water) periodicity, while in the upper river it was due only to diel periodicity.

The sampling program addressed spatial heterogeneity by taking samples in different ecological zones, at different transects within each zone to assess longitudinal variation, at different locations on each transect to assess lateral variation, and at different depths at each station to assess vertical variation. Temporal variation was considered by collecting samples at different times of the day, different phases of the tide, and at different times of the year. A commonly used design for this type of ecological survey would be a four level complete-block design (Winer 1971). Using a complete design the sampling program might consist of five zones with four transects within each zone, four stations per transect, and four depths at each station. This design should be repeated four times in each zone to cover the four combinations of tide and photoperiod: day flood, night flood, day ebb, and night ebb. The sampling must then be repeated four times throughout the year to cover the four different river stages: rising waters, flood stage, declining waters, and low stage. This yields a total of $5 \times 4 \times 4 \times 4 \times 4 \times 4 = 5{,}120$ samples not including possible replicates for quality control; this was a sampling program far in excess of the capability of the research team. But, by making some statistical assumptions, a more efficient sampling program, the Greco-Latin Square, was employed. This Latin Square provided a considerable reduction in the number of samples needed while allowing for testing of the relevant research hypotheses concerning spatial heterogeneity and temporal variation (Netter and Wasserman 1974). The major statistical assumption required for use of the Latin Square design is that there is no interaction among any of the main effect blocking variables (Winer 1971). By using a four-sided Greco-

Latin Square, only 16 samples were required in each zone to investigate the effects of transects, stations, depth, and temporal variation. This yielded an overall design with 5 zones x 16 samples x 4 seasons = 320 samples, a reduction of the total number of samples by 93.75%. This sampling scheme permitted collection of replicate samples and the incorporation of the other subprograms, while retaining the capability to test research hypotheses.

Within this Latin Square design, sampling for the ecological survey was conducted at two levels of effort, high-frequency and low frequency. Because analysis of most biological samples was time consuming, 320 samples plus replicates proved to be an upper limit for the ecological survey. These were considered "low frequency samples" and included samples for bacteria, phytoplankton, zooplankton, macro-invertebrates, fish larvae, and adult fish. The chemical and physical variables were easily measured compared to the biological variables, and hence a greater number of samples was collected and they were classified as "high frequency samples." High frequency sampling consisted of collection of 16 samples (one Latin Square) during each of the four time periods in each zone, which yielded a total of 1,280 samples. However, modifications to the sampling program reduced the total number of high frequency samples to 1,010. High frequency samples included: water temperature, pH, dissolved oxygen, alkalinity, suspended solids, conductivity or salinity, chlorophyll, and macro-nutrients (nitrate-nitrogen, dissolved silicon, soluble reactive phosphorus, total nitrogen, and total phosphorus). This document is restricted to the results of the high frequency sampling.

The guiding principle of sample collection was that the Greco-Latin Square defined the particular time, depth, and location of a sample. A representative sample was then taken from the designated location. Figure 2 is the

T1	L2	B3	U4
B4	U3	T2	L1
L3	T4	U1	B2
U2	B1	L4	T3

T=TOP
U=UPPER
L=LOWER
B=BOTTOM

1=FLOOD DAY
2=FLOOD NIGHT
3=EBB DAY
4=EBB NIGHT

FIGURE 2. Greco-Latin Square sampling design used during the October and December 1983 field trips.

Greco-Latin Square design used during the second and third field trips. In accordance with this design, a surface sample was collected during a daytime flooding tide at station one on transect one. The transect one - station one sample was collected during the day flood tide in each zone, i.e., the same Greco-Latin Square was repeated in each zone. In the upper river and headwaters zone, tide and depth factors were not present due to the absence of tide and a shallow well-mixed water column. In those zones, the four time periods were day, night, dawn, and dusk. Downstream, where depth was included in the design, the water column was divided into four parts and samples were collected as surface, upper, lower, and bottom. This overall sampling program was repeated four times in all zones except in the headwater zone, where it was repeated three times. In the headwater and upper river zones all samples were collected on a low frequency basis because of difficulties involved in processing, storage, and analysis of certain chemical variables in remote areas.

Use of the Greco-Latin Square design permitted testing of five hypotheses for each variable sampled. These hypotheses can be considered as the following set of questions: Were there differences among transects within a zone, among stations within a zone, among different depths, between day and night, and between ebb and flood tides as mentioned above? The statistical assumption required for these analyses was that there were no interactions between main effects (Winer 1971). Statistical tests were conducted to evaluate the extent to which this assumption was violated and subsequently affected the strength of the inferences.

The elegance of the sampling design used in this study was that a considerable amount of information could be gained outside of the Latin Square sta-

tistical framework with only a minimal amount of additional sample collection. In some cases no additional sample collection was required for additional hypothesis testing. For example, comparisons among different zones during one field trip were made by one-way Analysis of Variance (ANOVA). Likewise, comparisons among different field trips for any one zone were made by one-way ANOVA. The interaction of zones and field trips were made by two-way ANOVA.

Supplementary information about the lower portion of the Gambia River was obtained in order to enhance the overall understanding of the river ecosystems. Detailed studies were conducted during all four field trips of mangrove bolons in the vicinity of the upper estuary sampling site. The results of these studies were used to enhance the understanding of the interactions between the main river and surrounding mangroves. Another source of supplementary data was the collection of samples between the lower estuary and lower river sampling sites. Samples collected at approximately 4-km intervals from 1-m depth were used to characterize the transitions between zones and determine the boundaries between zones. These samples also served to chart the movement of certain key interfaces along the river over the course of the four field trips, e.g., the freshwater-saltwater interface was plotted with these sample.

METHODS

Sample Collection

Most samples were collected from small (7 m) boats using a 3.5-L Kemmerer bottle. The small boats were used in conjunction with the R/V *Laurentian* in the lower estuary, upper estuary, and lower river zones. In these locations, the small boats served as the primary sampling platforms while the R/V *Laurentian* provided the laboratory. Because the primary sam-

pling site in the lower estuary zone was over 40 km^2, sampling in that zone was conducted by both a small boat and the R/V *Laurentian*. Five-liter Niskin bottles were used to collect samples from the R/V *Laurentian*. Sample collection in the upper river and headwaters zone was conducted from a very small boat (4 m) or by wading into the river. A stream-side camp was used for the laboratory in these zones in lieu of the laboratory onboard the R/V *Laurentian*. Some samples collected from the upper river zones were packed on ice and brought to the R/V *Laurentian* for analysis. In extremely shallow portions of the river, samples were collected by holding plastic sample bottles below the surface of the water.

Immediately after the samples were collected from the river, the water was placed into a 2-L translucent plastic bottle and a 500-mL opaque bottle. The 2-L bottle was used to store samples for chlorophyll, suspended solids, soluble nutrients, and total nutrients. The opaque bottle stored samples for pH and alkalinity determinations. After these sample bottles were filled from the sample collection device, the bottles were stored in coolers until they were returned to the laboratory. Samples were usually brought to the laboratory within 1.5 hours of collection.

Dissolved oxygen measurements were primarily made with a YSI model 58 digital meter and a submersible probe on a 30-m cable. The oxygen meter was used to record *in situ* water temperatures. Conductivity and/or salinity measurements were made with a YSI model 33 conductivity meter with a submersible probe and a 30-m cable. Both oxygen and conductivity measurements were automatically temperature compensated by the meters. Salinity determinations on six samples were made with both the YSI model 33 meter and an induction salinometer at the Oceanographic Institute in Dakar. The salinity of these six

samples ranged from 1.5 ppt to 35 ppt. The results showed the YSI meter yielded readings from 0.4 to 1.3 ppt lower than the salinometer.

After the samples were returned to the laboratory, they were immediately processed for additional analyses. pH measurements were made within 1 hour of reaching the laboratory, followed by alkalinity titrations. While one technician conducted the pH and alkalinity determinations, a second processed the chlorophyll, soluble nutrients, suspended solids, and total nutrients samples. All but the total nutrients samples required filtration through GF/C or HA Millipore filters. Filtering was begun within 15 minutes of bringing the samples to the laboratory.

Temperature

Water temperatures were measured with either an expanded scale glass thermometer or a submersible probe. All water samples were placed into a 2-L sample bottle immediately after sample collection. Temperatures measured by the glass thermometer were recorded by placing the thermometer into the 2-L sample bottle as soon as it was filled. Air temperatures and water temperatures never differed by more than 5 C°; thermal inertia prevented water samples from changing temperature more than 0.1 C° between collection and before temperatures were measured with a glass thermometer.

The majority of water temperatures were measured in situ with a submersible probe. The thermistor in the dissolved oxygen probe was used for the temperature measurements. The model 58 YSI meter provided temperature readings on a digital read-out with an accuracy of 0.1 C°.

pH and Alkalinity

pH measurements were made with an Orion model 231 pH meter with a tem-

perature compensating probe. Determinations were made in the laboratory or at the stream-side field camp on fresh samples. Probes were soaked in sample water for at least 2 hours before a set of samples was analyzed. During the analysis of one set of samples, the pH probes were allowed to soak between 4 and 5 minutes in each sample. This soaking provided ample time for the pH reading to stabilize. The pH meter was calibrated against pH 7.00 and 4.00 buffers approximately 3 hours before each set of measurements.

Immediately following the pH measurements, samples were analyzed for alkalinity. From 50 to 200 mL of sample were titrated with either 0.02 or 0.04 N H_2SO_4. A 10-mL burret was used to titrate the sample which was constantly mixed by a magnetic stirrer. Two end points were determined on each sample, pH 5.1 and pH 4.5. Both end points were determined by the pH meter; probes were kept in the titrant throughout the entire titration process. Alkalinity was calculated from titration to pH 4.5 using the equation:

$$\text{Alk in mg } CaCO_3/L = \frac{\text{mL of acid} \times 50{,}000 \times N}{\text{mL of sample}}$$

Dissolved Oxygen

Dissolved oxygen concentrations were measured either with a submersible probe or by titration. Most dissolved oxygen determinations were made with a submersible probe attached to a 30-m cable and a YSI model 58 digital meter. The YSI meter was calibrated prior to each usage in the field. A saturated air calibration technique was employed. The meter was adjusted for battery drift and then adjusted to read 100% saturation in a closed flask which was half filled with water. Dissolved oxygen measurements were then made with the

meter, which provided temperature and salinity compensation. The meter would thus yield oxygen concentrations in both mg O_2/L and per cent saturation.

Oxygen measurements were also made by Winkler titration in several locations. Standard procedures (American Public Health Association 1982) were followed for these titrations. BOD bottles (300 mL) were carefully filled to over-flowing in the field immediately after the water samples were collected. Dissolved oxygen was fixed with 2 mL of manganous sulfate reagent followed by 2 mL of alkaline iodide solution. Oxygen samples were kept in the dark until titration, which was never more than 12 hours after collection. At least once per zone per field trip dissolved oxygen concentrations from one water sample were measured by both the YSI meter and Winkler titration. If the YSI meter could not be standardized to yield measurements within 0.1 mg O_2/L of the titrated value, the meter was not used in favor of titrations; only toward the end of the research project was the titration technique used in favor of the YSI meter.

Conductivity and Salinity

Conductivity and/or salinity measurements were made with a submersible probe attached to a 30-m cable. The probe and cable were used in conjunction with a YSI model 33 portable conductivity-salinity-temperature meter. The probe was lowered to a predetermined depth and the temperature of the water at that depth determined. The meter was adjusted for the temperature and the conductivity and/or salinity reading was made. In a few instances, salinity readings were made on-board the R/V *Laurentian* rather than *in situ*. At least 500 mL of sample water was placed in a plastic beaker, and the probe placed in the beaker. Salinity readings were then made in the same manner as in the field.

Suspended Solids

Samples for suspended solids were held in 2-L plastic bottles until they were brought onboard the R/V Laurentian or to the stream-side laboratory. Suspended solids samples were collected by filtering from 150 to 1,000 mL of river water through an oven-dried, preweighed GF/C filter. GF/C filters were prepared for suspended solids samples by drying numbered filters in a vacuum desiccator at 105°C for 24 hours. These filters were weighed on a Mettler model AE 163 electronic balance to the nearest 0.01 mg and then stored in aluminum foil envelops in a desiccator. A measured volume of river water was filtered with a moderate vacuum (20-25 psi). Filters were removed from the filtering apparatus, folded, and stored in glassine envelops. These filters were dried in the vacuum desiccator at 105°C and stored in a glass desiccator until analysis. The dried filters were reweighed on the Mettler balance and the difference between the original and final weights computed. The suspended sediment load was computed based on the sample weight and volume.

Chlorophyll and Phaeopigments

Chlorophyll samples were taken from the same 2-L plastic bottles as the suspended solids samples. From 150 to 500 mL of river water were filtered through a GF/C filter using a moderate vacuum of 20-25 psi. Damp filters were immediately transferred to dark brown glass vials which contained about 6 mL of a 90% acetone-water mixture. The acetone-water mixture had 1 mg $MgCO_3$ per each liter as a buffer to prevent pigment degradation during the storage. The vials with their filters were numbered and stored in the freezer at -20°C until analysis. Samples collected in the upper river and headwaters zones could not be immediately placed in a freezer. When possible, the vials were stored on ice until they reached the freezer. Headwaters zone samples were

kept on the filters until they were returned to the ship; this storage method caused some loss of chlorophyll via degradation to phaeopigment because of heat and desiccation, but was the only method available.

Chlorophyll samples were kept at -20°C until analysis, which varied from 20 hours to 3 weeks. Analysis began by grinding the GF/C filters with the algal cells in a glass grinding tube with a Teflon grinder. Normally 20-30 seconds of grinding reduced the filter and acetone-water solution to a pulp. The pulp was poured into a graduated centrifuge tube, and the contents of the tube brought up to 12-17 mL. Samples were placed in a refrigerator for 20 hours to allow further extraction.

After the 20-hour extraction, chlorophyll concentrations were measured with a Turner Designs model 10 fluorometer. Clear supernatant was removed from each centrifuge tube with a filter syringe and placed into a cuvette. Two fluorometric readings were made on each sample, one before and one after two drops of 50% HCl were added to the cuvette. The two readings were used to determine chlorophyll and phaeopigment concentrations. The fluorometer was set up for measuring extracted chlorophyll a with a blue lamp and the specified optical filters as recommended by Turner Designs. After the readings were made on the fluorometer, cuvettes were cleaned with two distilled water and two acetone rinses. The cuvettes were allowed to dry for at least 10 minutes after rinsing. Chlorophyll and phaeopigment concentrations were determined via the equations of Strickland and Parsons (1972).

Soluble Nutrients

Nitrate-nitrogen (NO_3-N), soluble reactive phosphate (PO_4-P), and soluble reactive silica ($Si(OH)_4$) were measured on a Technicon AutoAnalyzer II system. Water for soluble nutrient determinations was taken from the same 2-L

sample bottle as the chlorophyll and suspended solids samples. Soluble nutrient sample water was prepared for analysis by filtering through an HA Millipore filter (0.45 μm) which had been soaked in deionized water for at least 3 days. Approximately 30 mL of river water were filtered as a prerinse for the HA filter. The prerinse water was discarded and from 100 to 250 mL of river water were filtered for the soluble nutrient analyses. Some of this filtered water was used to fill a 30-mL plastic bottle, which was first rinsed three times, to overflowing. These bottles were stored for 48 hours or less in a refrigerator before analysis.

Soluble nutrient samples collected from the headwaters zone were processed with basically the same procedure. The samples were stored in ice chests after collection until they were brought to the stream-side laboratory. These samples were analyzed on a Hach DREL/3 field analysis kit at the stream-side laboratory. Soluble nutrient samples collected in the upper river zone were stored on ice until they could be brought to the R/V Laurentian for analysis with the AutoAnalyzer II system.

Standard AutoAnalyzer methods were followed for the three nutrient determinations. The NO_3-N method followed Armstrong et al. (1967) with a Cd reduction of nitrate to nitrite-nitrogen. The PO_4-P method employed the stannous chloride method of Murphy and Riley (1962). The $Si(OH)_4$ technique used the silicomolybdate method of Strickland and Parsons (1972). Analogous Hach kit methods were used for samples collected in the headwaters zone.

Quality control was a major aspect of all automated nutrient analyses. A rigorous regime of standards and blanks was used besides the usual replication of 20% of the samples. Standards which encompassed the expected nutrient concentrations were analyzed before and after each run of twenty samples.

Deionized water blanks were inserted between the standards and samples as well as after ten samples. Nutrient samples were randomized as much as possible rather than ordered within each run to prevent bias in interpretation of results. Final nutrient concentrations were computed from the absorbence values of the blanks, standards, and samples.

Total Nutrients

Samples for total phosphorus (TP) and total nitrogen (TN) were also analyzed on the Technicon AutoAnalyzer. Unfiltered river water was poured into graduated, screw-top test tubes. These tubes were stored at -20°C for up to 5 months before analysis. Sample analysis began by thawing the frozen samples in the test tubes, followed by a persulfate digestion for TP and an alkaline persulfate digestion for TN. Digestion was achieved by placing the tubes with added persulfate into an autoclave for 20 minutes. After digestion the NO_3-N method and the PO_4-P method were used to analyze the samples with the AutoAnalyzer. The TN method followed D'Elia et al. (1977) and the TP method followed Menzel and Corwin (1965). The same system of standards and blanks used for analysis of the soluble nutrients was also used for the total nutrients.

Data Processing

Preliminary data analysis was conducted between each field trip. Field results were entered into Apple IIe personal computers as soon as possible after the field trip was completed. Field data were converted to meaningful values and stored in a data matrix in a database management system. Information regarding the location and time of collection of each sample was combined with the analytical results to form a flat file data matrix for each

of the four field trips. Data input was then verified by comparing the computer-stored results to the original log sheets or instrument charts. These verified data were then considered ready for analysis.

An intermediate level of data analysis was carried out in Africa using the Apple IIe computers. This analysis included computation of descriptive statistics (minimum and maximum values, mean, standard deviation, standard errors, and range) by strata (by zones and by field trips) for each variable. An additional level of analysis was conducted with ANOVA statistical models. Two forms of Latin Square ANOVAs were used to determine the importance of spatial and temporal variability on each of the physical and chemical variables. The final level of data analysis was conducted in Ann Arbor using the University of Michigan computing system. Data were transferred directly from the Apple IIe computers to the mainframe computer. Data analysis was primarily conducted using the MIDAS statistical package (Fox and Guire 1976).

HYDROLOGY OF THE GAMBIA RIVER BASIN

The planning and design of dams for the Gambia River have required an extensive understanding of the hydrology of the basin. Studies conducted by a variety of European consultants began as early as 1975 and will continue well into the future as planning proceeds. As a result of the numerous reports, general hydrological knowledge about the Gambia River Basin is relatively good. But, a lack of data prevents the formation of reliable long-term trends. In order to develop an adequate understanding of the basin-wide hydrology, the existing data base was supplemented by sampling conducted during the Gambia River Basin Study. In particular, data concerning water temperature, salinity, conductivity, and suspended solids were collected in 1983 and 1984. A synopsis of the hydrologic data is given below, which provides the basic facts concerning the water characteristics of the basin.

GENERAL DESCRIPTION OF THE CLIMATE

The Gambia River Basin is a semi-tropical region located between 11° 30' and 15° 00' North latitude and 11° 00' and 16° 30' west longitude. The basin covers 77,100 km^2 of which 13%, 72%, and 15% lie in The Gambia, Senegal, and Guinea respectively (Fig. 1). The basin has three distinct geographic regions; a hilly upper watershed in Guinea, a rolling continental basin in Senegal and the eastern half of The Gambia, and a very flat coastal plain in the western half of The Gambia. The principal source of water to the Gambia River is rainfall in the upper watershed and southeastern continental basin.

Climatological data for the basin were collected at a variety of locations, but were primarily derived from eight stations in the basin. The historical record is quite variable but begins as early as 1919 for rainfall and

as late as 1975 for evaporation data (Harza 1985). The climate of the basin is characterized as semi-tropical with distinct wet and dry seasons. The wet season begins in March or April in the upper watershed and moves slowly North to begin in June or July in the northern continental basin. The wet season ceases in September in the north and October or November in the south. Winds during the rainy season are prevailing southwesterlies and carry high moisture content from the Atlantic Ocean. The dry season occupies the remaining portion of the year and is characterized by a virtual absence of rain. Dry season winds are easterly, northeasterly, or northerly and carry large quantities of dust and silt from the North African deserts; these are called Harmattan Winds. The annual cycle of wet and dry seasons depends on the formation and migration of a low pressure zone called the Intertropical Convergence Zone.

Air temperatures in the basin follow a seasonal pattern with annual minimums in December and January, and maximums in April or May. The daily mean minimums in the basin are about 15 to 17°C, while the mean maximum approaches 40°C. Temperatures in the highlands of the upper watershed are slightly (3-5C°) cooler. Daily sunshine averages from 5 to 6 hours during the rainy season to over 9 hours in March. Mean relative humidity on the continental basin ranges from 30% in January to over 80% in June. Humidity along the coast rarely falls below 50%. Winds are generally light and variable during the early dry season (0.8 m/s in November) to moderate just prior to the annual rains (2.4 m/s in May); winds are calmer inland compared to coastal areas. Evaporation rates in the basin are high (approx. 2,500 mm/year), but vary considerably between December (about 4.5 mm/day) and May (about 9.5 mm/day). Evapotranspiration, estimated by Coode and Partners et al. (1974)

and Agrar-und Hydrotechnik GMBH and Howard Humphreys Ltd. (AHT/HHL) (1983), was also high and typically the same or slightly more than evaporation.

As mentioned above, rainfall is distinctly seasonal throughout the basin as well as occurring in a south to north gradient. For the 1928-1981 average, rainfall ranged from 1,600 mm/yr in the southern reaches of the watershed to less than 600 mm/yr in northeastern areas (Harza 1985) (Fig. 3). February or March is the driest month of the year and August the wettest. Monthly rainfall averages range from 0.0 mm in February or March to over 500 mm in August. 1983, the year of the Gambia River Basin Study field investigations, was one of the driest years in history. Rainfall ranged between 20 and 70% of the long-term average, constituting a one-in-one-hundred-year drought. Central Gambia near Kuntaur was the driest portion of the basin in 1983.

WATER TEMPERATURE

The primary source of water temperature data was from field observations made during the Gambia River Basin Study. Those data showed distinctly different annual trends in each of the five zones sampled. In the lower estuary sampling, zone water temperature was influenced primarily by the prevailing ocean temperature. During the rainy season field trips (August and October), the water temperature in the lower estuary remained close to 30°C and then dropped to slightly above 23°C for the December and March field trips (Fig. 4). This reflected the change in the ocean temperature caused by the shift in the North Equatorial current.

Temperatures in the upper river zone were the most variable of the five zones, both among field trips and within field trips. Among the four field trips a range of 12.5C° was observed (20.5°C during low water and 33°C during high water). Ranges of 8.9C° and 8.5C° were observed within the declining and

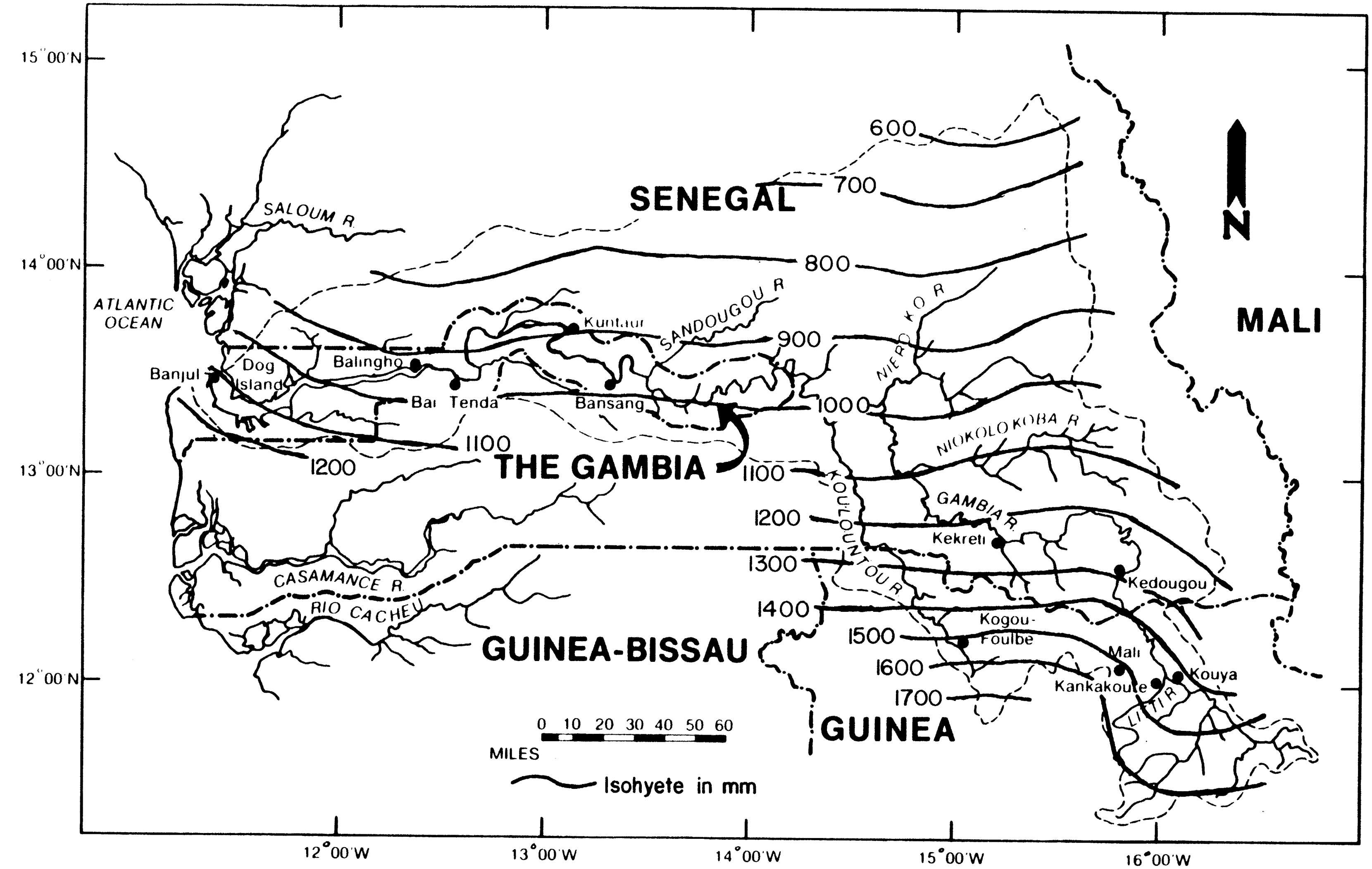

FIGURE 3. Average annual rainfall in the Gambia River Basin. Isohyetes are in mm rain per year and represent a 53-year average from 1928 to 1981 (from Harza 1985).

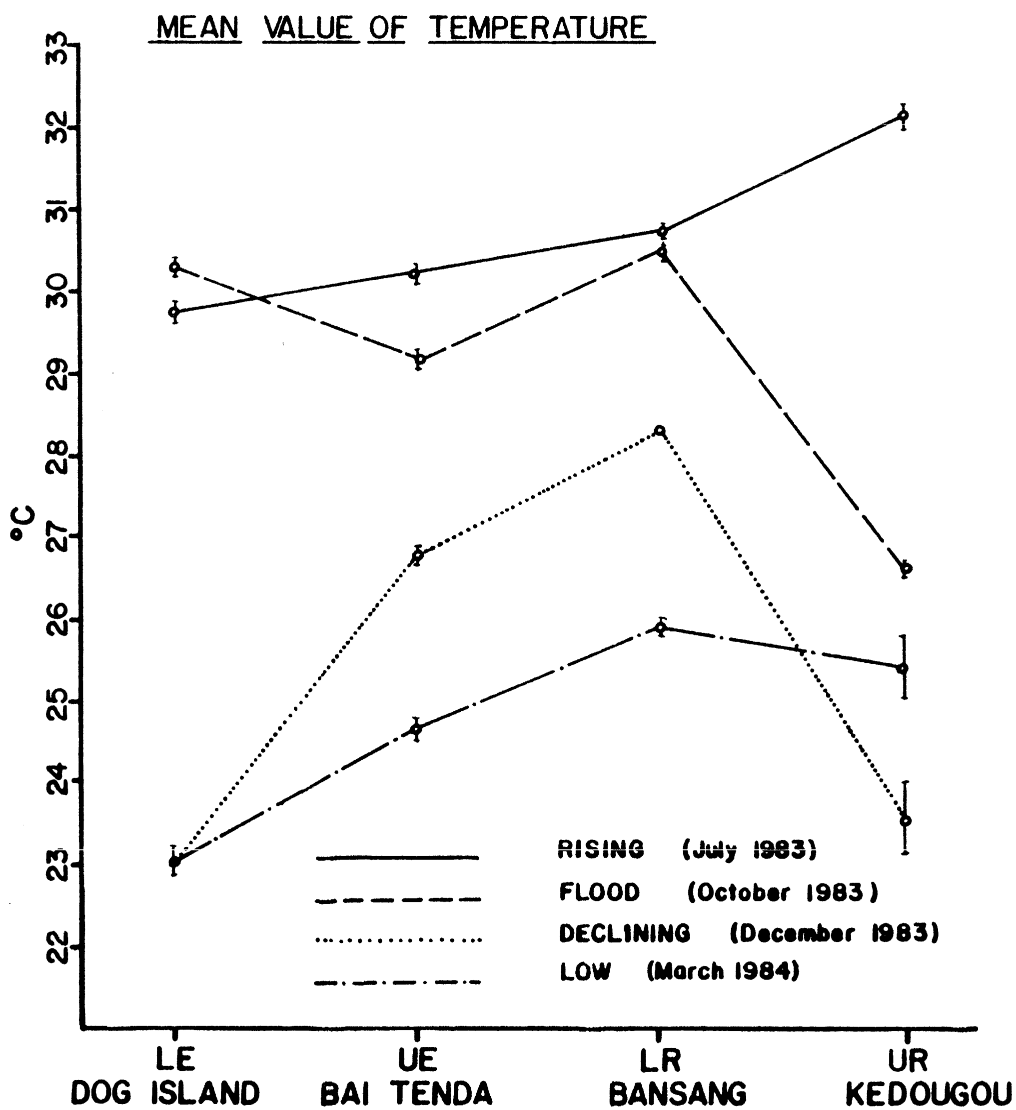

FIGURE 4. Mean water temperatures and standard errors for each zone and season.

low water field trips respectively (Table 1). The highest variability within one field trip occurred when water levels were low and there were large differences between day and night air temperatures.

Temperatures in the lower river were consistently higher than temperatures in the upper estuary. This difference ranged from 0.5C° for the rising water period (August) to 1.3C° for the flood (October), declining (December), and low water (March) periods. Temperatures in both these zones decreased for each successive field trip. This decrease was 4.6C° for the upper estuary zone from the rising water period (July) to the low water period (March) and 4.9C° for the upper river during the same period.

During the rising water period average water temperatures increased with distance upstream from a minimum of 29.7°C in the lower estuary to a maximum of 32.2°C in the upper river. Temperatures during the flood water period did not increase monotonically with distance upstream, but rather ranged from 26.6°C in the upper river zone to 30.5°C in the lower river zone (Table 1). The greatest variation in mean temperatures among zones was observed during the declining water period (lower estuary 23.1°C, upper estuary 26.8°C, lower river 28.2°C, upper river 23.5°C). Temperatures during the low water period were distributed in a similar pattern as the declining water period, but with reduced magnitude in differences among zones (lower estuary 23.0°C, upper estuary 24.6°C, lower river 25.9°C, and upper river 25.5°C).

Seasonal changes in water temperatures in the upper estuary and lower river occurred more slowly than in the lower estuary and upper river. The magnitude of seasonal changes in water temperatures was also less in the upper estuary and lower river zones compared with the other two zones. In general, water temperatures were constant with depth, with the exception of occasional

TABLE 1. Water temperature (C) results from the Gambia River, 1983 and 1984.

Minimum

	Rising	Flood	Declining	Low	
Lower Estuary	28.50	29.00	20.80	22.10	20.80
Upper Estuary	29.90	28.80	26.10	23.60	23.60
Lower River	30.00	30.20	27.80	25.00	25.00
Upper River	30.50	26.20	20.80	20.50	20.50
	28.50	26.20	20.80	20.50	20.50

Maximum

	Rising	Flood	Declining	Low	
Lower Estuary	31.00	33.00	25.00	24.40	33.00
Upper Estuary	31.00	29.50	27.50	26.20	31.00
Lower River	31.20	30.90	28.80	28.00	31.20
Upper River	33.00	27.00	29.70	29.00	33.00
	33.00	33.00	29.70	29.00	33.00

Mean

	Rising	Flood	Declining	Low	
Lower Estuary	29.74	30.32	23.07	22.98	25.96
Upper Estuary	30.24	29.17	26.84	24.64	27.66
Lower River	30.77	30.51	28.24	25.88	28.80
Upper River	32.15	26.59	23.53	25.45	26.62
	30.58	29.79	25.77	24.60	27.45

Standard Deviation

	Rising	Flood	Declining	Low	
Lower Estuary	.62	.86	.71	.41	3.59
Upper Estuary	.23	.13	.32	.56	2.18
Lower River	.21	.24	.26	.63	2.02
Upper River	.62	.28	3.34	2.21	3.97
	.78	1.13	2.52	1.45	3.01

Coefficient of Variation

	Rising	Flood	Declining	Low	
Lower Estuary	2.10	2.80	3.10	1.80	13.80
Upper Estuary	.80	.50	1.20	2.30	7.90
Lower River	.70	.80	.90	2.40	7.00
Upper River	1.90	1.10	14.20	8.70	14.90
	2.50	3.80	9.80	5.90	11.00

minor daytime heating of the surface layer in all zones during all seasons which indicated that complete vertical mixing of the water column had occurred.

STREAMFLOWS

Streamflow data for the Gambia River Basin are extremely sparse. In The Gambia, all water level gages are affected by the tides; because discharge measurements are not taken, streamflows cannot be estimated. The station at Gouloumbou provides the farthest downstream streamflow data, approximately 525 km upstream, or half the total length of the river. Streamflow records from Gouloumbou extend back to 1952. Eight water level gages and 16 staff gages were installed in Senegal along the Gambia River and its tributaries between 1972 and 1978. Seven gages are in place in Guinea; two automatic recorders and five staff gages, all installed during 1975-76. The streamflow database has many gaps despite the installation of new equipment. For example, there are still no high flow rating curves. Flow duration curves have been calculated for the river at Kedougou and Gouloumbou from the gage data, and simulated for the Sandougou and Koulountou locations (AHT/HHL 1983).

Streamflows in the Gambia River and its tributaries respond directly to rainfall, but have marked regional differences. In the upper watershed annual runoff is about 25% of annual precipitation, which drops to 10% for the continental basin and 1-2% for the coastal plain.

Despite the rather sparse historical streamflow database, 11 locations on 9 different tributaries have provided enough information to compute average flows for the period 1970-1982. These are presented in Table 2 by monthly averages. The results show that the Gambia, Koulountou, and Sandougou rivers have year-round flow. The recent drought has caused all rivers except the

TABLE 2. Average monthly streamflows for the Gambia River and tributaries (from Harza 1985).

Station Name	River	Drainage Area (km^2)	M	J	J	A	S	O	Mean Flow in m^3/s N	D	J	F	M	Annual		Period	Source
Kedougou	Gambia	7550	0.4	12.4	74.3	315.3	323.2	138.2	42.4	19.5	10.5	5.3	2.2	0.6	79.1	1970-1982	b
PNNK	Niokola Koba	3000	0.2	1.7	9.2	22.1	31.3	10.4	1.4	0.2	0.0	0.0	0.0	0.0	6.4	1970-1982	a, b
Bridge	Thiokoye	950	0.0	1.5	9.7	29.3	39.3	16.8	3.8	1.1	0.4	0.1	0.0	0.0	8.5	1970-1982	a, b
Bridge	Diarha	760	0.0	1.2	9.1	25.4	29.7	14.5	2.1	0.6	0.2	0.0	0.0	0.0	6.9	1970-1982	a, b
Bridge	Sima	495	0.0	0.1	0.4	0.5	1.0	0.4	0.2	0.1	0.1	0.0	0.0	0.0	0.2	1970-1982	a, b
Wassadou U/S	Gambia	21200	0.5	7.6	97.1	429.1	582.4	269.4	70.1	25.2	10.7	4.7	1.7	0.6	124.9	1970-1982	a, b
Confluence	Nieriko	11950	0.2	5.6	21.2	40.8	56.9	19.4	2.7	0.4	0.1	0.0	0.0	0.0	12.3	1970-1980	a
-	Koulountou	1900	0.1	0.6	2.2	17.3	21.8	6.9	5.2	1.0	0.5	0.2	0.1	0.1	4.2	1970-1980	a, b
Niaoule-Tanou	Niaoule	1230	0.0	0.4	0.9	0.8	0.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1970-1982	a, b
Gouloumbou	Gambia	4200	3.1	14.1	115.4	510.8	720.9	402.5	118.9	40.4	15.0	7.9	4.5	3.6	163.7	1970-1982	a, b
	Sandougou	12000	0.4	3.9	14.0	9.6	9.7	2.0	0.9	0.5	0.2	0.1	0.1	0.1	3.6	1970-1982	b

NOTES: a) Source: Kekreti Reservoir Project, Project Definition Report. Annex C, Hydrology and Reservoir Operation Studies August, 1983.

b) Direction des Etudes, Hydrauliques, Tambacounda.

Gambia to cease to flow during the late dry season. Table 3 shows the 1983 streamflows and the percent of the long-term average. The extent of the 1983 drought is evident from these data; verbal histories indicate that the 1970-82 period was dry compared to the first half of the 20th century, thus making the 1983 drought loom even more severe over the long term. Tables 2 and 3 also show the seasonal nature of streamflows, with the annual flood always cresting in September.

The annual flood of the Gambia River provides a considerable amount of water which inundates a large area. Between 1953 and 1983 flood water levels at Gouloumbou rose an average 9.1 meters above dry season levels with a range of 2.8 to 13.8 meters. Despite steep banks, overtopping is common during floods, especially on the coastal plain. The small flood of 1983 did not provide sufficient water to overtop most upstream banks.

TIDES AND CURRENTS

The coastal plain and western edge of the continental basin through which the Gambia River flows are extremely flat with an average slope of 0.02 m/km. The river in this area is wide and funnel-shaped from its mouth at Banjul to Balingho, approximately 135 km upstream. The river is an average 10 km wide near Banjul and decreases exponentially with distance to 2 km wide at Balingho. Above Balingho the river meanders for the next 100 km and then follows a narrower channel to the upper watershed. The Gambia River decreases in width from 2 km at Balingho to 100-150 m above Bansang. The decrease in width is approximately linear with distance.

The wide river running through flat terrain allows the propagation of tidal waves up to 530 km upstream, just above Gouloumbou. Tidal ranges include full coastal tides at Banjul (average of 1.68 m) to 10 cm at Gouloumbou

TABLE 3. Average 1983 monthly streamflows for the Gambia River and percent of long-term average (from Harza 1985).

Station Name	River	Drainage Area (km^2)	M	J	J	A	S	O	N	D	J	F	M	A	Annual
Kedougou	Gambia	7550	n.a.	4.7	34.3	118.0	183.7	81.7	20.0	10.7	4.7	1.9	n.a.	n.a.	39.0[a]
Percent of Long Term		Average	-	38	46	37	57	59	47	55	45	36	-	-	49
Wassadou	Gambia	21200	0.2	5.7	55.3	120.0	255.0	99.2	24.4	9.0	3.4	1.3	0.4	n.a.	47.9[b]
Percent of Long Term		Average	40	66	62	24	41	39	36	34	31	27	24	-	37
Gouloumbou	Gambia	42000	0.3	14.8	64.2	126.0	295.0	134.0	46.1	20.3	13.4	5.0	1.3	0.4	59.1[c]
Percent of Long Term		Average	10	95	56	25	41	33	39	5.0	89	63	29	11	36

NOTES: a) Source: Direction des Etudes Hydrauliques, Tambacounda. Unpublished values.

b) Some dry season flows near 0.0 m^3/s missing.

c) Some dry season flows affected by tidal influence estimated.

during the dry season. Tidal dynamics within the river have been described and modelled by the Hydraulics Research Station (HRS) (1977) and Rhein-Ruhr Ingenieur-Gesellschaft (RRI) (1984). Since the early 1970s, nineteen water level recorders on the river in The Gambia have provided an extensive database for analysis of tidal dynamics.

The dynamics of the tides in the river are rather complex for several reasons. First, the great length of the tidal portion of the river and the semi-diurnal period allow two tidal waves to exist in the river at one time. Second, tidal waves do not appear to be reflected from the flat river banks but rather their energy is gradually damped throughout the river except for a few zones of amplification (HRS 1977). Third, tidal ranges are diminished in the segment between Georgetown and Gouloumbou during the annual flood. Despite these complex factors, tidal dynamics have been modelled and the results are shown in Table 4. This table shows that tidal waves take almost 1 day (22 h, 20 m) to propagate from Banjul to Gouloumbou, at an average speed of 563.5 km/day. Tidal ranges remain large throughout most of the tidal portion of the river, exceeding 1 meter up to Bansang, just over 300 km upstream.

Tidal harmonics (period of tidal oscillations) produce strong reversing currents in the Gambia River. These currents are asymmetrical in their strength, with ebb tide currents exceeding flood currents. The Danish Hydraulic Institute (1982) estimated maximum ebb tide currents at up to 0.9 m/s and maximum flood currents at 0.7 m/s; these estimates were supported by observations during the Gambia River Basin Study. The harmonics of the tides cause water in the river to oscillate upstream and downstream. But, the stronger ebb currents lead to net downstream flow which matches streamflows at

TABLE 4. Tidal characteristics of the Gambia River (from Harza 1985).

Station	Distance from Banjul in km	Mean Time of Propagation h	min	Average range in m
Banjul	-	0	00	1.68
Tendaba	103	4	32	1.52
Balingho	130	5	36	1.33
Brumen Bridge	132	5	40	1.70
Pakaliba Bac	184	7	54	0.90
Kaur	199	8	24	1.30
Chamen Bac	228	9	39	0.93
Kuntaur	254	10	36	1.44
Jahally	270	11	30	1.33
Patchar	282	11	54	1.25
Georgetown	295	12	30	1.19
Bansang	312	13	24	1.08
Sami Tenda	362	15	24	0.89
Basse	404	17	10	0.82
Fatoto	478	20	18	0.65
Gouloumbou	525	22	20	0.10

Gouloumbou (Howard Humphreys Ltd. (HHL) 1974). An additional aspect of tidal harmonics is the presence of an unusual 2-week downstream tidal surge in the vicinity of Bansang. Field studies by HRS (1977) showed that net downstream flow almost stops during neap tides, but then surges once every 2 weeks with the spring tides. Tidal waves also assist in seasonally flooding low-lying lands adjacent to the Gambia River.

Observations made during the Gambia River Basin Study indicated certain specific attributes in regard to tides and currents in each zone. In the lower estuary, currents were very complex. Reversal of the tidal stream did not occur at the same time for all points along the transverse axis of the river. For example, the flood current began along the southern shore while the ebb current continued along the northern shore. Due to its large area and

fetch of several kilometers, the lower estuary zone was susceptible to the formation of wind-generated waves. While waves of 0.75 m to 1 m were commonly observed, wave activity was most pronounced in the months of February and March when the wind had a predominantly westerly component.

In the upper estuary during the flood waters sampling period, currents of 2.75 km/hr for the flood tide and 3.50 km/hr for the ebb tide were observed. The tidal front moved in a V-shaped manner, with tidal reversal occurring at the center of the river before it occurred near the banks. Reversal of the tidal stream in the bolons occurred at the times of high and low water, about 2 hours earlier than tide reversal in the river. Areas of turbulence were produced at the entrances of bolons when the current in the bolon was ebbing while the current in the river was still flooding and vice versa. Waves of 0.25 m were encountered at least once during all field trips. Typically, waves were generated by the wind blowing against the tidal stream and lasted a short period of time.

In the lower river, currents followed the tidal regime of the river. During the flood sampling period, maximum mid-river currents of 0.74 km/hr for the flood tide and 2.1 km/hr for ebb tide were observed. Longitudinally the Gambia River in the upper river zone was characterized by alternating sections of rapids and laminar flow. The river in this zone was not affected by tidal forces, and water levels and currents were determined primarily by runoff, ground water seepage, and evaporation rates. During the rising waters period (June), the maximum depth at mid-channel was 1.5 m. The increased runoff associated with the rainy season increased maximum water depths to 4 m during the flood sampling period (October). Many areas were flooded at this time and river currents were quite strong and turbulent. By the declining water stage

(December) the water level had receded to a maximum depth of 2 m. There were also areas where it was possible to cross the river with a maximum depth of 1 m. Current velocities were also greatly reduced.

SALINITY AND CONDUCTIVITY

The propagation of tidal waves over 500 km up the Gambia River and the low dry season streamflows allows saltwater to penetrate the river as far as 250 km upstream. Saltwater intrusion is a fundamental aspect of the ecology of the river. The extent and duration of the intrusion controls the nature of the aquatic flora and fauna as well as the amount of crops grown along the river.

Given the importance of salinity in the estuary, HHL conducted an extensive field study of saline water movements from 1972 to 1974. Their results (HHL 1974) were further verified by models and field data (HHL 1984). The details vary among years because of the magnitude of the annual flood, but a basic pattern has emerged. On a longitudinal basis, salt water migrates upstream each year during the dry season to a recent maximum penetration of about 250 km. The salt frontier (boundary between fresh and salt water) reaches its maximum penetration in early June and remains more or less stationary until mid-August. The annual flood rapidly pushes the salt frontier downstream to its minimum penetration in September. That location depends greatly upon the size of the flood, but recently has been between 70 and 130 km above the river mouth (1973 and 1984 respectively). Verbal historical records indicate the salt frontier moved downstream as far as the river mouth during the larger floods of the first half of the century. After the passage of the flood, salt water begins to move back upstream in late October. Between October and June, the salt frontier moves upstream at an average rate

of 15 km/month, increasing toward 20 km/month at the end of the dry season. The flood pushes the frontier over 125 km downstream in about 5 weeks. Longitudinal salinity gradients range from 0.40 ppt/km (parts per thousand/km) to 0.17 ppt/km in September and May respectively (HHL 1974). Figure 5 shows the migration of salinity during the HHL study.

Many estuaries develop a typical salt wedge where fresh water overlays denser salt water (McLusky 1971). The Gambia River with its low dry season streamflows does not exhibit this phenomenon between October and August. But, during the peak of the annual flood, a distinct salt wedge was observed by the HHL study. Both vertical and longitudinal salt wedges were observed between 50 and 90 km upstream. Figures 6 and 7 show dry and flood season salinity cross-sections with the salt wedge evident in Figure 7. Further, Coriolis forces cause more saline water to accumulate along the left or south bank. Observations during the Gambia River Basin Study indicated that flood tides tended to move upstream along the left bank.

Throughout the estuary, tidal waves create oscillations of water in the river. As a result, observations at a fixed location on the river bank show a cycle in the salinity. Salinities appear to increase during flood tides and decrease during ebb tides.

Field measurements of salinities taken during the Gambia River Basin Study concurred with values reported above. The maximum extent of the estuary was observed during the July field trip when its upper boundary existed near Kuntaur, 250 km upstream from Banjul (Fig. 5). In October during the annual flood, the freshwater-saltwater interface was observed 141 km from Banjul. This time of the year represented the minimum extent of salt water into the Gambia River. During the declining river stage in December the estuary

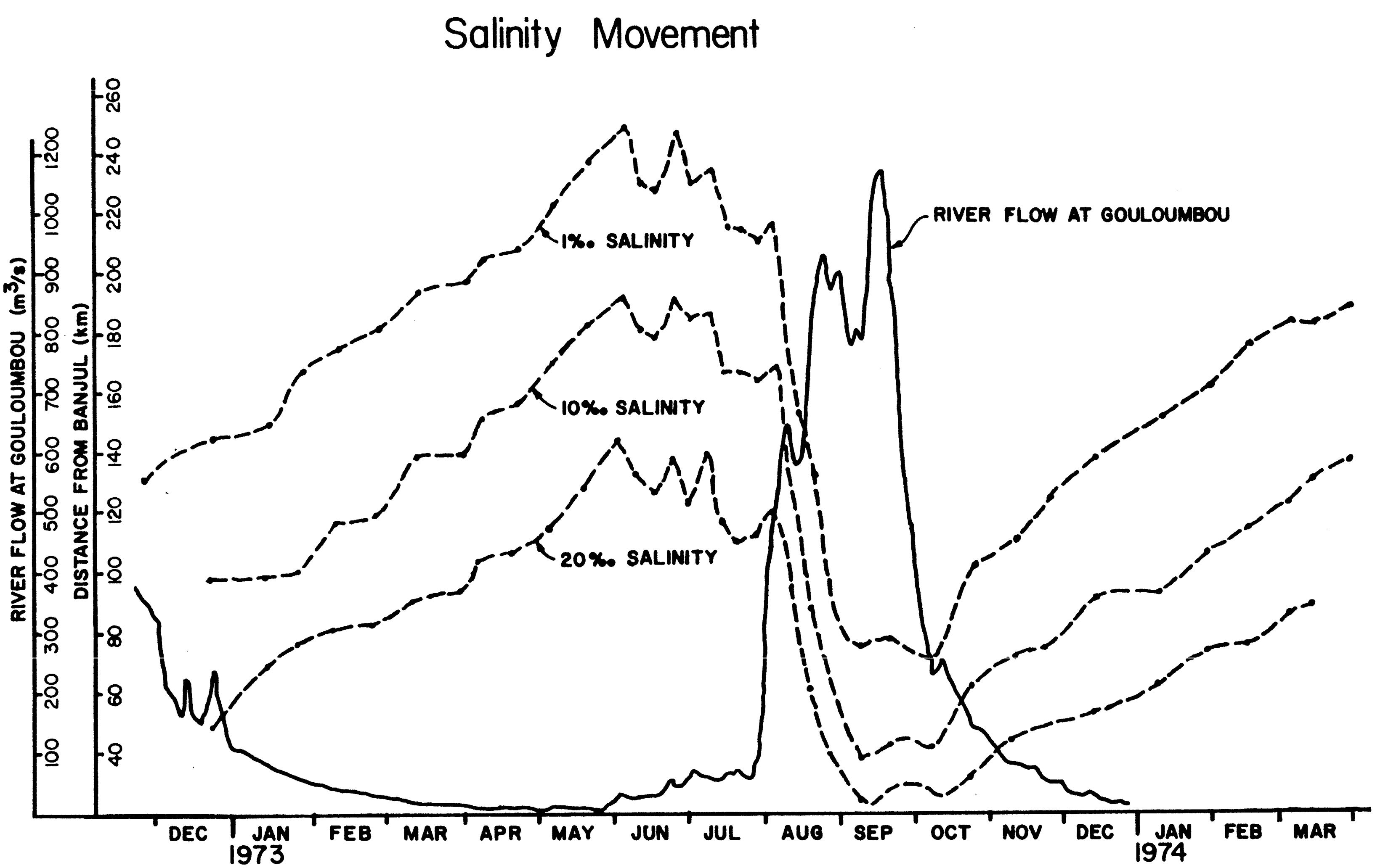

FIGURE 5. Longitudinal movement of salinity throughout the year in the Gambia River estuary compared to streamflows at Gouloumbou.

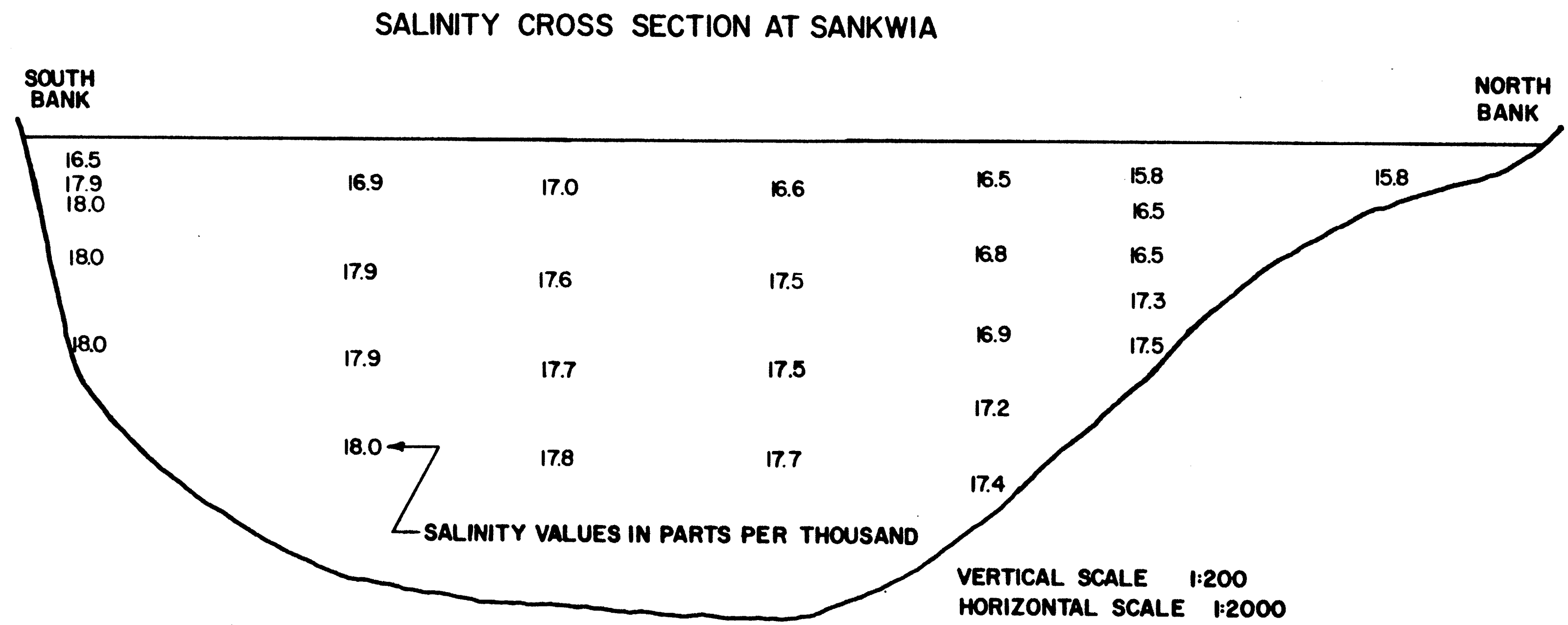

FIGURE 6. Salinity cross-section in the Gambia River during late July 1973. Cross-section is 142 km upstream from Banjul.

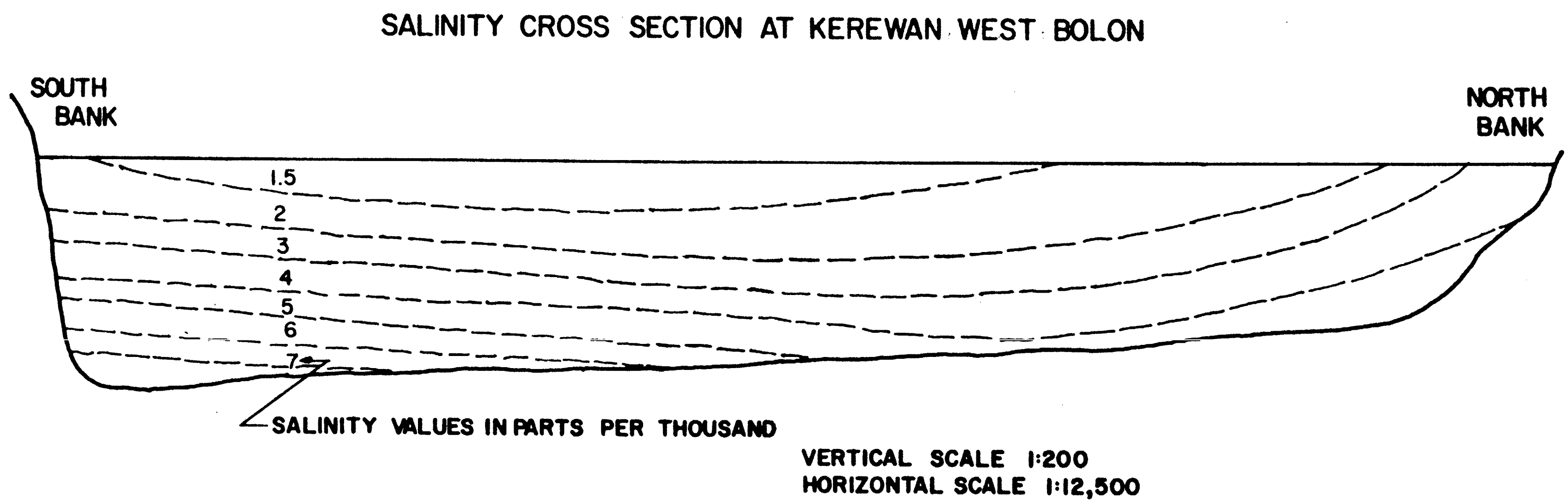

FIGURE 7. Salinity cross-section in the Gambia River during early October 1973. Cross-section is 72 km upstream from Banjul.

lengthened to 156 km. This boundary proceeded up the river as the water receded, and during the March field trip was observed 207 km from Banjul (Fig. 5). Saltwater intrusion was defined as the point at which conductivity increased precipitously with distance down river. This point was observed at 259 km from Banjul in July, at 218 km in October, at 224 km in December, and at 250 km in March (Fig. 5).

The lower estuary sampling, located approximately 12 km from the river mouth, underwent only slight salinity changes during the course of the field studies. The maximum mean value of 34.1 ppt was observed in July and the minimum mean value of 32.4 ppt occurred in October (Table 5). The annual mean salinity value for the lower estuary was 33.3 ppt. The upper estuary site, located near Bai Tenda, 145 km from Banjul, was saline throughout the most of the year except during periods of maximum river discharge. The mean value observed in July was 13.7 ppt. This declined to 0.2 ppt in October, and increased to 2.2 ppt in December and 11.2 ppt in March (Table 5). Throughout the course of the study an average salinity of 8.1 ppt was observed at the upper estuary sampling site.

At the freshwater sampling sites low conductivities were observed throughout the course of the field work. All sites showed the same trend in conductivity with river stage, similar to the trends in salinity found in the estuary (Fig. 8). In July the upper and lower river zones had a mean conductivity (25°C) of 89.2 and 91.1 μmhos/cm respectively. As the water level in the river rose, the mean conductivity decreased to the lowest observed values of 35.0 μmhos/cm for the upper river zone and 42.0 μmhos/cm for the lower river zone in October. Conductivity increased at both of these sites throughout the declining and low water river stages; by the March field

TABLE 5. Salinity results (ppt) from the Gambia River, 1983 and 1984.

Minimum

	Rising	Flood	Declining	Low	
Lower Estuary	28.70	29.50	31.50	33.40	28.70
Upper Estuary	12.20	.10	1.40	9.90	.10
Lower River	0.00	0.00	0.00	0.00	0.00
Upper River	0.00	0.00	0.00	0.00	0.00
	12.20	.10	1.40	9.90	.10

Maximum

	Rising	Flood	Declining	Low	
Lower Estuary	33.80	34.00	35.30	34.80	35.30
Upper Estuary	14.50	.30	3.00	12.10	14.50
Lower River	0.00	0.00	0.00	0.00	0.00
Upper River	0.00	0.00	0.00	0.00	0.00
	33.80	34.00	35.30	34.80	35.30

Mean

	Rising	Flood	Declining	Low	
Lower Estuary	33.01	32.37	33.48	34.07	33.27
Upper Estuary	13.67	.23	2.15	11.21	8.10
Lower River	0.00	0.00	0.00	0.00	0.00
Upper River	0.00	0.00	0.00	0.00	0.00
	19.62	25.44	17.62	22.64	21.07

Standard Deviation

	Rising	Flood	Declining	Low	
Lower Estuary	1.18	1.02	.81	.32	1.07
Upper Estuary	.57	.06	.39	.59	5.36
Lower River	0.00	0.00	0.00	0.00	0.00
Upper River	0.00	0.00	0.00	0.00	0.00
	9.01	13.32	15.73	11.48	13.15

Coefficient of Variation

	Rising	Flood	Declining	Low	
Lower Estuary	3.60	3.20	2.40	.90	3.20
Upper Estuary	4.20	27.80	18.30	5.20	66.10
Lower River	0.00	0.00	0.00	0.00	0.00
Upper River	0.00	0.00	0.00	0.00	0.00
	45.90	52.30	89.30	50.70	62.40

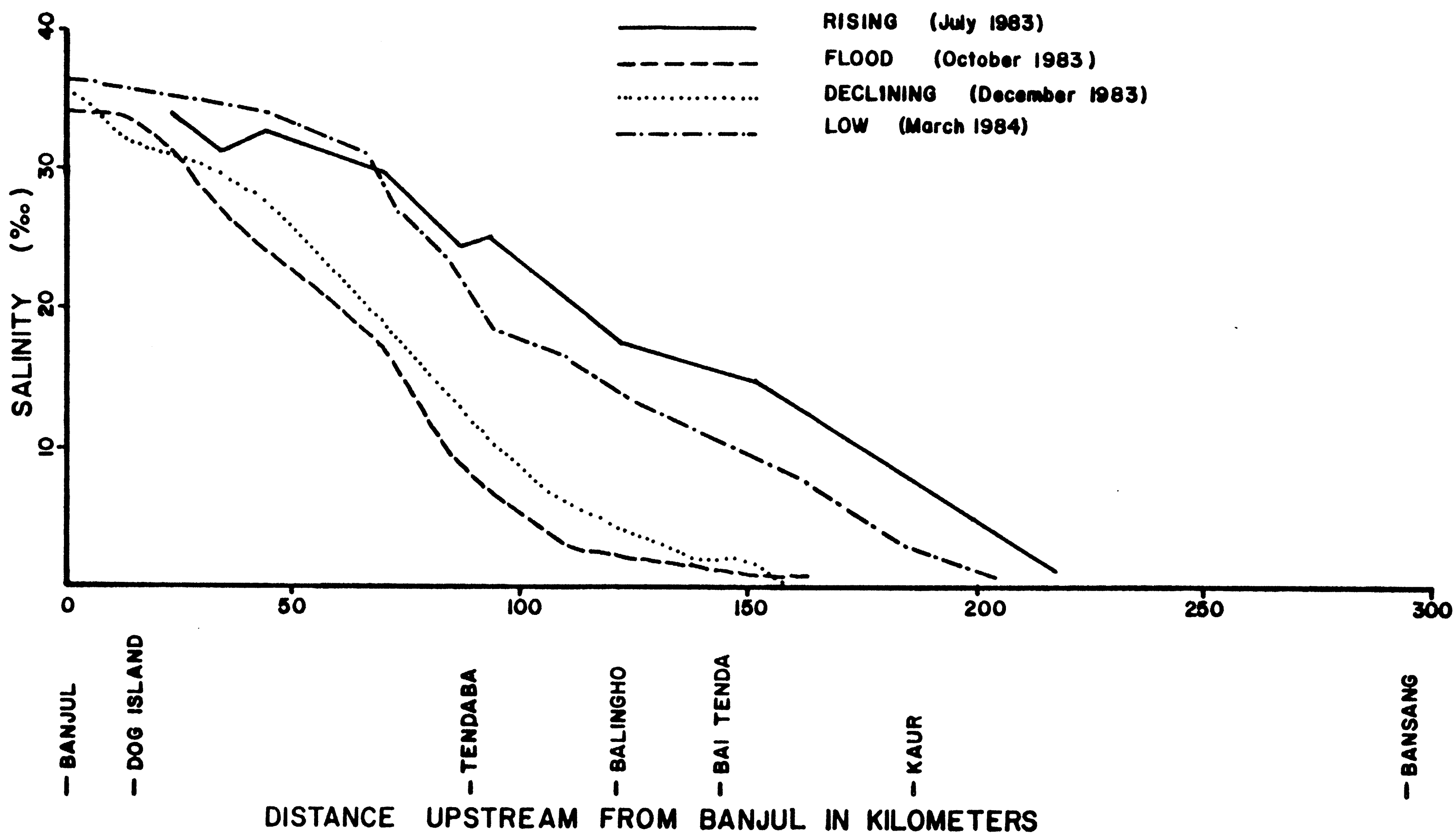

FIGURE 8. Distribution of salinity by season in the lower 300 km of the Gambia River.

trip the mean value had not reached the levels observed in July (Table 6). The annual mean conductivity in the Gambia River was 59.5 μmho/cm for the lower river and 54.7 μmho/cm for the upper river.

SEDIMENTS AND SUSPENDED SOLIDS

The Gambia River carries a relatively low sediment load due to its armored bottom and low streamflows during the dry season (Harza 1985). The best long-term sediment database is available from observations by ORSTOM (1978) beginning in 1974. The best spatial database was assembled by the Gambia River Basin Study which includes over 20 locations in the river. The results of these two databases agree very well.

Spot samples collected in between the major sampling sites showed areas of high suspended solids which appeared in different parts of the river depending on the amount of freshwater discharge. In all cases except the field trip, the region of high suspended solids began with a rapid increase in suspended solids near the saltwater-freshwater interface and continued up into the freshwater section of the river. The lowest level of suspended solids was observed during the July field trip. An annual maximum was reached during the flood stage field trip and receded during the declining and low water studies (Fig. 9).

The average suspended solids values in mg/L at the four sampling sites over the course of the study were 84 for the lower estuary, 75 for the upper estuary, 25 for the lower river, and 45 for the upper river (Table 7). Suspended sediment loads in the Gambia River are extremely low during the dry season, never exceeding 50 mg/L in the freshwater portion of the river. The annual flood brings an increase with runoff, and suspended sediment loads averaged about 100 mg/L. AHT/HHL (1984) calculated the total sediment load

TABLE 6. Conductivity results from the Gambia River, 1983 and 1984.

Minimum

	Rising	Flood	Declining	Low	
Lower Estuary	0.00	0.00	0.00	0.00	0.00
Upper Estuary	22800.00	790.00	3000.00	16100.00	790.00
Lower River	85.00	42.00	44.00	48.00	42.00
Upper River	87.00	35.00	35.00	50.00	35.00
	85.00	35.00	35.00	48.00	35.00

Maximum

	Rising	Flood	Declining	Low	
Lower Estuary	0.00	0.00	0.00	0.00	0.00
Upper Estuary	26000.00	1000.00	4970.00	19700.00	26000.00
Lower River	92.00	54.00	51.00	57.00	92.00
Upper River	104.00	50.00	40.00	55.00	104.00
	26000.00	1000.00	4970.00	19700.00	26000.00

Mean

	Rising	Flood	Declining	Low	
Lower Estuary	0.00	0.00	0.00	0.00	0.00
Upper Estuary	24061.97	847.69	3925.00	17996.25	11350.21
Lower River	89.21	50.61	49.68	51.57	59.53
Upper River	91.08	41.81	36.34	51.75	54.67
	10281.49	412.12	1662.17	7687.63	4915.57

Standard Deviation

	Rising	Flood	Declining	Low	
Lower Estuary	0.00	0.00	0.00	0.00	0.00
Upper Estuary	812.12	55.98	625.50	879.36	9568.05
Lower River	1.85	1.81	1.48	2.27	16.41
Upper River	4.69	5.24	1.79	1.90	21.69
	11898.42	400.53	1959.19	8914.28	8402.68

Coefficient of Variation

	Rising	Flood	Declining	Low	
Lower Estuary	0.00	0.00	0.00	0.00	0.00
Upper Estuary	3.40	6.60	15.90	4.90	84.30
Lower River	2.10	3.60	3.00	4.40	27.60
Upper River	5.10	12.50	4.90	3.70	39.70
	115.70	97.20	117.90	116.00	170.90

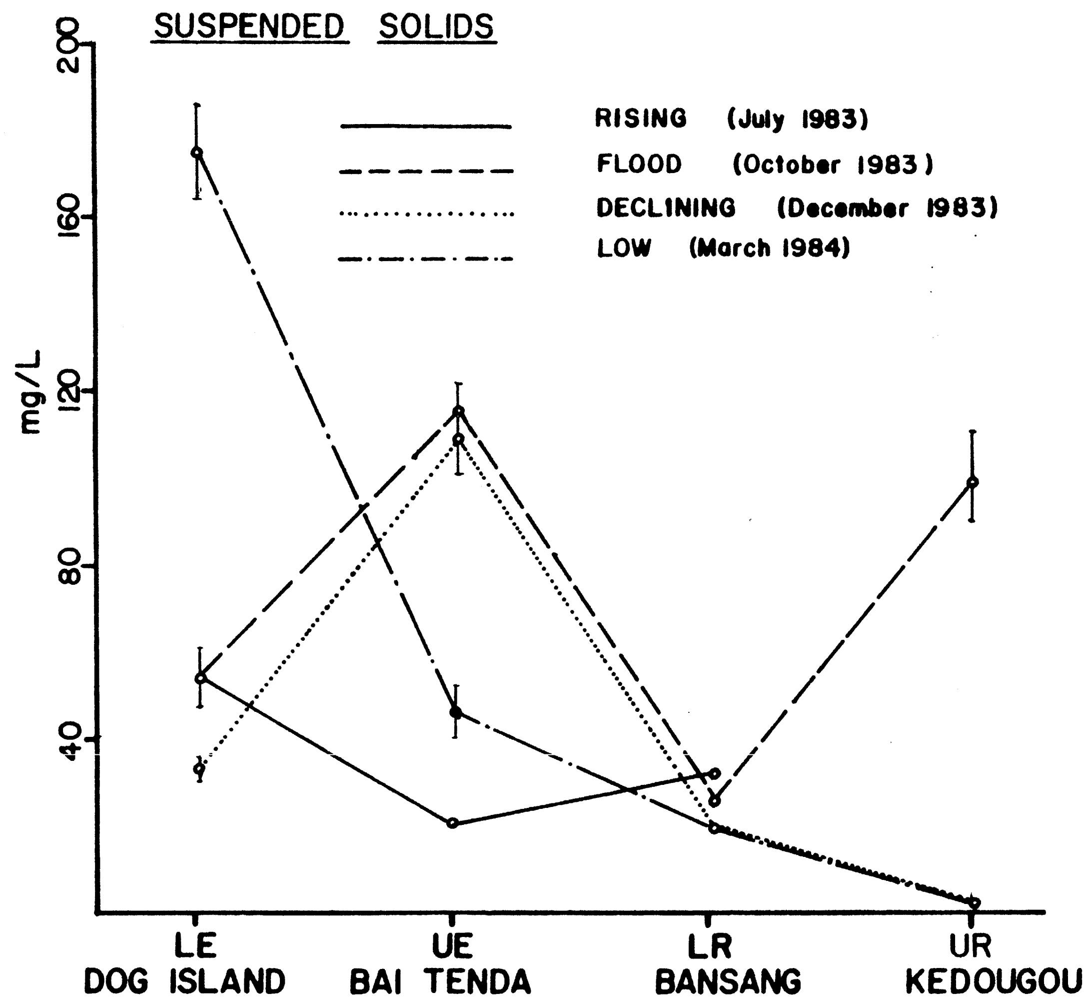

FIGURE 9. Mean suspended solids concentrations and standard errors for each zone and season.

TABLE 7. Suspended solids results (mg/L) from the Gambia River, 1983 and 1984.

Minimum

	Rising	Flood	Declining	Low	
Lower Estuary	18.76	23.46	7.58	33.22	7.58
Upper Estuary	11.16	75.92	23.25	13.60	11.16
Lower River	25.04	19.50	14.00	14.65	14.00
Upper River	0.00	32.44	1.34	.92	.92
	11.16	19.50	1.34	.92	.92

Maximum

	Rising	Flood	Declining	Low	
Lower Estuary	219.52	129.30	190.00	517.20	517.20
Upper Estuary	44.14	223.60	498.20	469.42	498.20
Lower River	44.00	50.10	46.74	25.75	50.10
Upper River	0.00	189.95	3.96	1.94	189.95
	219.52	223.60	498.20	517.20	517.20

Mean

	Rising	Flood	Declining	Low	
Lower Estuary	54.22	52.28	33.35	174.87	83.78
Upper Estuary	20.34	116.37	111.64	45.80	75.30
Lower River	33.34	25.73	20.53	20.19	24.75
Upper River	0.00	101.58	2.37	1.32	44.53
	31.89	69.01	49.31	76.75	58.89

Standard Deviation

	Rising	Flood	Declining	Low	
Lower Estuary	39.72	23.68	32.64	100.86	85.42
Upper Estuary	7.58	27.57	95.38	55.69	70.91
Lower River	3.84	5.13	4.18	2.20	6.56
Upper River	0.00	59.36	.66	.30	62.70
	21.23	47.13	68.86	94.17	67.82

Coefficient of Variation

	Rising	Flood	Declining	Low	
Lower Estuary	73.30	45.30	97.90	57.70	102.00
Upper Estuary	37.30	23.70	85.40	121.60	94.20
Lower River	11.50	19.90	20.40	10.90	26.50
Upper River	0.00	58.40	27.80	22.50	140.80
	66.60	68.30	139.60	122.70	115.20

reaching the Kekreti as 265,000 tons/yr. Suspended sediment concentrations in Guinea were extremely low, usually less than 20 mg/L.

Suspended sediment loads in the estuary are higher than the freshwater segment of the river, typically exceeding 100 mg/L. These higher sediment loads were attributed to tidal currents scouring soft bottom sediments. Suspended sediment concentrations were particularly high during spring tides. Although suspended sediment loads were high in the estuary, net downstream movement was moderate. River and bolon bottoms were covered with a thick layer of soft material which was at least 25 m thick at Balingho.

GROUNDWATER

Although an extensive groundwater survey has not been conducted in the Gambia River Basin, the basic structure of the aquifers is known (Harza 1985). The four major aquifers are: Shallow, Eocene Sand, Maestrichtian Sand, and Hardrock. The Shallow Aquifer underlies all of The Gambia and part of Senegal Oriental. Water depths range from 0 to 50 m. The Eocene Sand Aquifer begins along the southern boundary of the basin and extends into the Cassamance region of Senegal. Water depths begin between 50 to 100 m. The Maestrichtian Sand Aquifer is found under the entire basin, with water depths from 0 m in eastern Senegal to over 500 m at the coast. Hardrock Aquifers are found throughout the basin, but their areal extent is variable and not totally known. The Maestrichtian Sand Aquifer is the most important source of ground water. Its transmissivity ranges from 2×10^{-4} to 4×10^{-2} m^2/s (Harza 1985).

CHEMICAL CHARACTERISTICS OF THE GAMBIA RIVER

NITRATE-NITROGEN

Nitrate-nitrogen, the predominant inorganic soluble nitrogen species in the Gambia River, made up more than 20% of the total nitrogen. The average percent nitrate for world rivers is 17% (Maybeck 1982). The average nitrate-nitrogen concentration for the Gambia River of 66.5 μg/L was low when compared to other unpolluted tropical rivers (Maybeck 1982). Observed values over the course of the study covered over three orders of magnitude from below the limit of detection (0.1 μg/L) to over 200 μg/L (Table 8 and Fig. 10). Nitrate-nitrogen concentrations in the Gambia River varied widely, both spatially and temporarily. Nitrate concentrations in the upper estuary zone were significantly higher than the other zones. The concentrations in the river were influenced greatly by zone (location along the river), season (time of the year), discharge (streamflows), saltwater intrusion or mixing, and algae uptake. They were influenced to a lesser extent by location at the sampling site (transect, station, depth) and tide.

The apparent major source of nitrate-nitrogen was from runoff; as a result its introduction from the catchment basin to the river is seasonal. The highest concentrations observed were generally during the annual flood (Fig. 10). Yet, these values were often lower than the world average for unpolluted rain of 175 μg/L (Meybeck 1982). Hence, there likely was no net contribution from the land except in the lower reaches of the river. Autochthonous sources produced in the framework of the nitrogen cycle were considered relatively small based on the continuous decline in nitrate-nitrogen concentrations following the annual rains. Loading of nitrate-nitrogen for Kedougou near the proposed Kekreti dam site was estimated to be 25,683 kg/yr and for Bansang

TABLE 8. Nitrate-nitrogen results (μg/L) from the Gambia River, 1983 and 1984.

Minimum

	Rising	Flood	Declining	Low	
Lower Estuary	.30	.66	.74	3.00	.30
Upper Estuary	38.51	196.04	197.07	28.77	28.77
Lower River	34.85	75.71	.01	.01	.01
Upper River	.01	.01	0.00	.06	.01
	.01	.01	.01	.01	.01

Maximum

	Rising	Flood	Declining	Low	
Lower Estuary	22.57	51.95	74.17	31.66	74.17
Upper Estuary	78.82	235.28	210.73	63.58	235.28
Lower River	121.90	101.98	4.07	.25	121.90
Upper River	85.00	23.93	0.00	14.29	85.00
	121.90	235.28	210.73	63.58	235.28

Mean

	Rising	Flood	Declining	Low	
Lower Estuary	7.65	22.93	54.54	24.36	30.61
Upper Estuary	66.83	218.41	204.34	42.79	134.69
Lower River	74.19	91.90	1.38	.02	41.43
Upper River	49.18	9.76	0.00	4.70	14.27
	58.36	100.64	88.26	20.30	66.54

Standard Deviation

	Rising	Flood	Declining	Low	
Lower Estuary	6.92	13.01	16.98	5.53	20.10
Upper Estuary	9.69	7.13	3.21	10.01	79.74
Lower River	28.64	7.05	1.48	.04	44.29
Upper River	37.40	8.44	0.00	2.62	22.81
	31.87	82.90	87.15	18.56	71.40

Coefficient of Variation

	Rising	Flood	Declining	Low	
Lower Estuary	90.40	56.70	31.10	22.70	65.70
Upper Estuary	14.50	3.30	1.60	23.40	59.20
Lower River	38.60	7.70	106.80	189.40	106.90
Upper River	76.10	86.40	0.00	55.90	159.90
	54.60	82.40	98.70	91.40	107.30

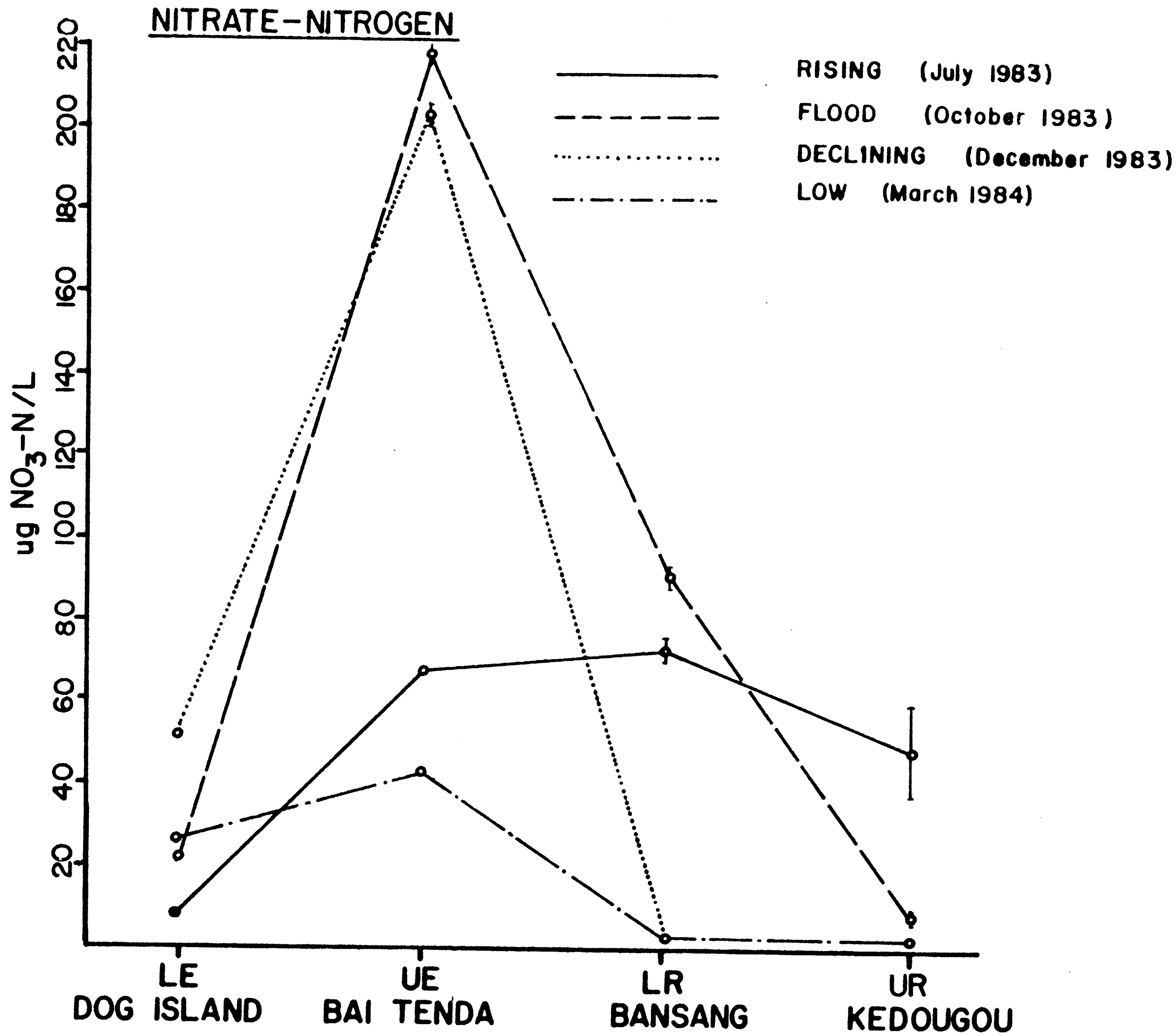

FIGURE 10. Mean nitrate-nitrogen concentrations and standard errors for each zone and season.

145,310 kg/yr. These loading results should be interpreted using the following considerations: 1) the estimates were calculated from only four field trips, 2) there was very low rainfall in 1983-84 (mean discharge 59.1 m^3 sec^{-1}), and 3) the levels may be affected by the reactive nature of the nitrogen cycle (total nitrogen may be better to use for ecological inferences). Higher loadings would occur with higher precipitation and vice-versa. The loss rates for the catchments above Kedougou and Bansang were almost identical (3.40 and 3.46 kg km^{-2} yr^{-1} respectively). This suggested similar edaphic factors with respect to nitrate for the catchments. The higher concentrations observed in the lower half of the estuary subbasin indicted higher nitrate-nitrogen loading.

The losses of nitrate from the river were from transport to the ocean and algal uptake. During the long dry season, levels of this major nutrient were reduced to near or below the limit of analytical detection. These levels are considered limiting to eukaryotic algal production and give an advantage to blue-green algae (Paerl and Kellar 1978).

The lower reaches of the Gambia River can be partitioned into different regions based on nitrate-nitrogen concentrations (Fig. 11). Throughout most of the year, a region of comparatively low nitrate-nitrogen concentrations extended from the river mouth to approximately 30 km upstream paralleling the marine-like lower estuary zone. This region encompassed the lower estuary sampling site which had an estimated yearly average nitrate concentration of 30 μg/L. The mean concentrations for each of the field trips at this site ranged from 8 to 54 μg/L. Throughout the study, this section of the river was greatly influenced by low-nitrate water from the ocean.

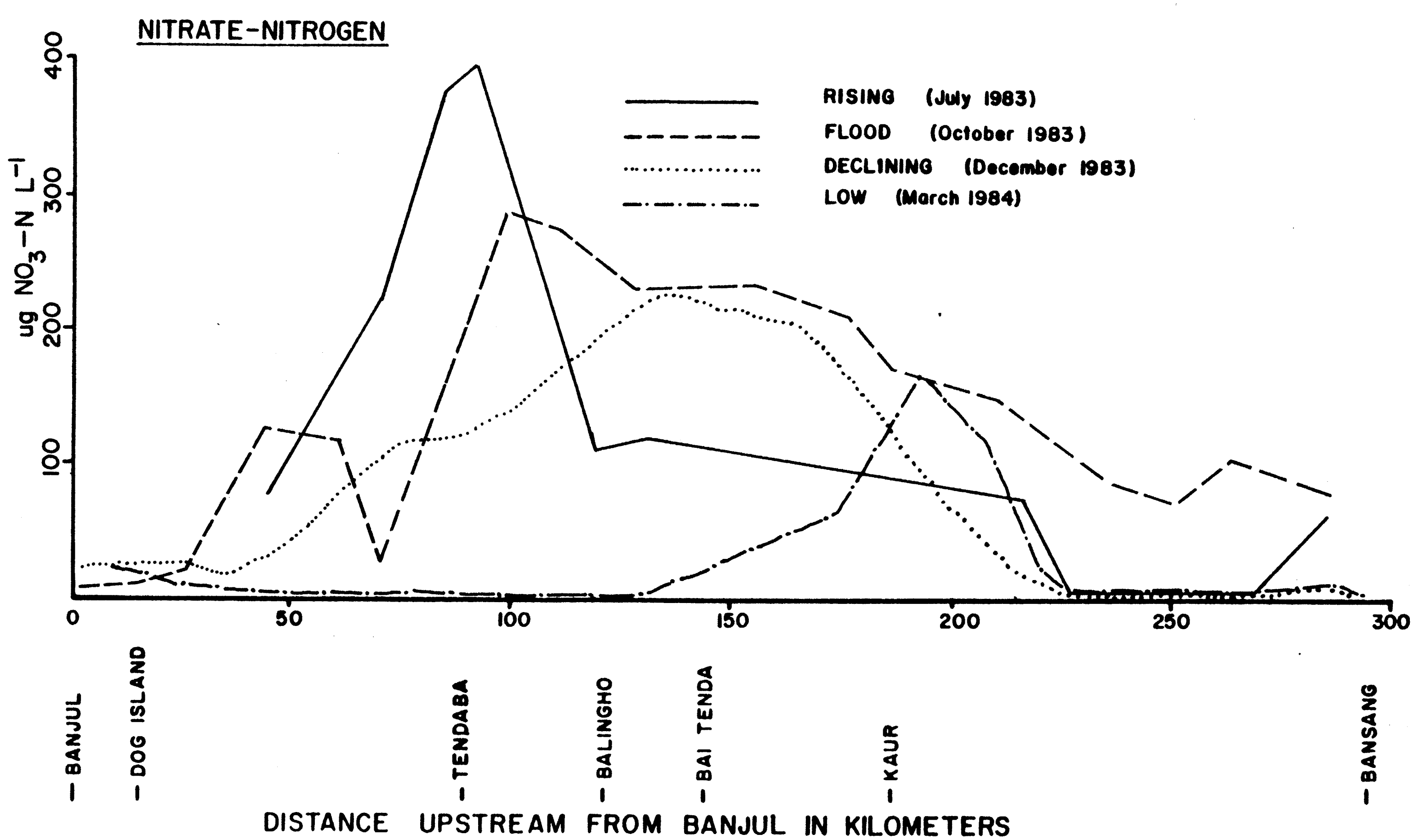

FIGURE 11. Distribution of nitrate-nitrogen by season in the lower 300 km of the Gambia River.

A region of comparatively high nitrate-nitrogen was apparent from 50 to 250 km from the river mouth (Fig. 11). Nitrate concentrations in this section of the river suggested that there were inputs of nitrate-nitrogen coming from local sources and/or the catchment in this part of the estuary. The highest observed values during the entire study (388 and 399 μg/L) were measured in July at 87 and 93 km upstream from the river mouth. Considering the large dilution by the low nitrate salt water, there evidently were extremely high nitrate waters entering the river at this location probably as a result from early rainy season runoff. The upper estuary sampling site, which had an estimated yearly average nitrate-nitrogen concentration of 118 μg/L, was contained near the middle of this high nitrate zone. The mean concentration for all field trips at this site ranged from 43 to 218 μg/L (Table 8). This high nitrate region was reduced to its smallest size in March, which was most likely due to transport of nitrate to the ocean, intrusion of low nitrate salt water, and algal uptake.

During the flood, declining, and low water stages there was a significant negative correlation of nitrate-nitrogen with salinity ($P<.01$), i.e., the system approached one which could be considered the mixing of two discrete solutions (Fig. 10). The relationship between salt water and nitrate was most evident during the declining water stage. Because nitrate-nitrogen from runoff had not completely flowed through the river at the time of the flood stage field trip, a lower correlation was observed than during the declining water stages. Algal uptake and/or lack of runoff had reduced much of the nitrate-nitrogen by the time the low water sampling had taken place, resulting in a low correlation between salinity and nitrate.

A region that contained no measurable nitrate-nitrogen for most of the year extended from about 225 km to 275 km upriver and approached the lower river sampling site at Bansang (Fig. 11). The estimated yearly average of nitrate-nitrogen at Bansang was 41 μg/L. The mean concentrations for the field trips at this site ranged from >.1 μg/L to 122 μg/L. The low concentrations in this area were probably due to a number of factors including lower concentrations of nitrate-nitrogen in runoff from upriver and algal depletion.

The estimated yearly average nitrate-nitrogen concentration at Kedougou was 14 μg/L. The mean concentrations from the field trips at this site ranged from 4.7 to 49 μg/L (Table 8).

Nitrate-nitrogen input to the river, transport down the river, and annual succession in the river can be examined by following nitrate-nitrogen concentrations through the field trip at each sampling sites (Table 8 and Fig. 10). The discharge which peaked in September, in between the rising water field trip in July and the flood water field trip in October, produced a rather rapid injection of solutes into the river. This sudden increase in nutrients can be compared, by analogy, to the overturn of a monomitic lake, when the highest values that will be observed occur at one time. This was seen in June by the overnight rise in nitrate concentration at Kedougou from <1 μg/L to approximately 100 μg/L following a local rain. By the time the river was sampled in October, the rains had ceased and the rainy season runoff had resided in the river environment for up to 2 months since the last sampling. During the flood stage sampling, nitrate concentration had increased compared to those which were observed in July at all sampling sites except the lower estuary.

The discharge measured for the declining water field trip in December was close to that found during the July field trip. The runoff from the rainy season had resided in the riverine environment for around 2 months. At this time, the nitrate-nitrogen concentrations had declined from the flood stage levels at all sites except the lower estuary where the increase from runoff was finally observed. This increase followed the freshwater pulse that was observed in October. The movement of a nitrate pulse from runoff can be traced down the river from Kedougou to the ocean by observing the sequence of peak values at the various sites: upriver (June), lower river and upper estuary (October), and lower estuary (December). During the December field trip, nitrate concentrations in the upper estuary had only slightly decreased while the lower river site had declined to near 1 μg/L (Table 8).

At the time of the low water field trip (March), the discharge was barely measurable and remained low until the next rainy season. Because 6 months had passed since the annual rains, any nitrate inputs came from ground water. However, significant inputs of high nitrate ground water were not observed. Due to the reactive nature of nitrate, inputs could have occurred and not been measured. In March, the river could have been considered in a state analogous to summer stagnation in the lentic environment. At all locations except the lower estuary, the lowest nitrate-nitrogen values over the course of the study were observed. The lowest values for the lower estuary were observed in July before runoff had reached that section of the river.

SOLUBLE REACTIVE SILICA

Soluble reactive silica (SRS) is one of the predominant solutes in the freshwater portion of the Gambia River (Lesack et al. 1984). The estimated average SRS concentration for the river was 9.2 mg/L (Table 9). Observed

TABLE 9. Soluble reactive silica results (mg/L) from the Gambia River, 1983 and 1984.

Minimum

	Rising	Flood	Declining	Low	
Lower Estuary	1.12	1.08	1.19	.61	.61
Upper Estuary	8.55	11.73	14.76	11.47	8.55
Lower River	2.17	13.67	11.41	14.84	2.17
Upper River	7.60	10.92	11.49	13.43	7.60
	1.12	1.08	1.19	.61	.61

Maximum

	Rising	Flood	Declining	Low	
Lower Estuary	2.24	4.94	2.31	1.27	4.94
Upper Estuary	8.97	13.53	15.79	13.55	15.79
Lower River	6.59	14.88	12.89	15.30	15.30
Upper River	9.70	13.21	12.61	14.21	14.21
	9.70	14.88	15.79	15.30	15.79

Mean

	Rising	Flood	Declining	Low	
Lower Estuary	1.35	1.76	1.66	.85	1.41
Upper Estuary	8.79	13.10	15.40	12.43	12.54
Lower River	3.95	14.32	12.65	15.09	11.68
Upper River	8.72	12.10	11.65	13.69	12.06
	5.63	9.97	10.15	9.99	9.21

Standard Deviation

	Rising	Flood	Declining	Low	
Lower Estuary	.25	.48	.31	.19	.51
Upper Estuary	.13	.29	.28	.63	2.36
Lower River	1.51	.42	.19	.13	4.43
Upper River	.72	.85	.18	.18	1.54
	3.10	5.42	5.61	5.97	5.55

Coefficient of Variation

	Rising	Flood	Declining	Low	
Lower Estuary	18.50	27.30	18.70	21.90	36.00
Upper Estuary	1.40	2.20	1.80	5.00	18.80
Lower River	38.20	2.90	1.50	.80	37.90
Upper River	8.30	7.00	1.60	1.30	12.80
	55.00	54.30	55.30	59.80	60.30

values over the course of the study ranged slightly over one order of magnitude from 0.61 mg/L in the lower estuary to 14.8 mg/L upriver. Standard deviations and coefficients of variation for the samples taken at the various study sites during a field trip were for the most part small (Table 9). Silica concentrations were about an order of magnitude lower in the lower estuary zone than in other zones. SRS concentrations in the Gambia River varied both spatially and temporarily (Fig. 12). The concentrations in the river were influenced greatly by zone (location along the river), season (time of year), discharge (streamflows), saltwater intrusion and mixing, and algal uptake. The concentrations were influenced to a lesser extent by location at the sampling site (transect, station, depth) and tide.

The major source of SRS was runoff. Thus, introduction of SRS to the river was for the most part seasonal. Higher concentrations were generally associated with high water (flood) stages. In the freshwater portions of the river the highest concentrations were found in March, which indicated concentration via evaporation and/or contribution from ground water, which in eastern Senegal were around five times higher in SRS than the average concentration found in the Gambia River (Harza 1985). The loading of soluble reactive silica at Kedougou was estimated to be 13,421 metric tons yr^{-1} and at Bansang 19,900 metric tons yr^{-1} for 1983-84. These loading results should be interpreted using the following considerations: 1) the estimates were calculated from only four field trips, and 2) the low rainfall in 1983-84. The Bansang estimate was approximately three times less than that estimated by Lesack et al. (1984) of 63,000 metric tons yr^{-1} for 1980-81. The difference can almost totally be accounted for by the two and one half times lower discharge in 1983-84 (1983-84 mean discharge 59.1 $m^3\ s^{-1}$, 1980-81 discharge 146

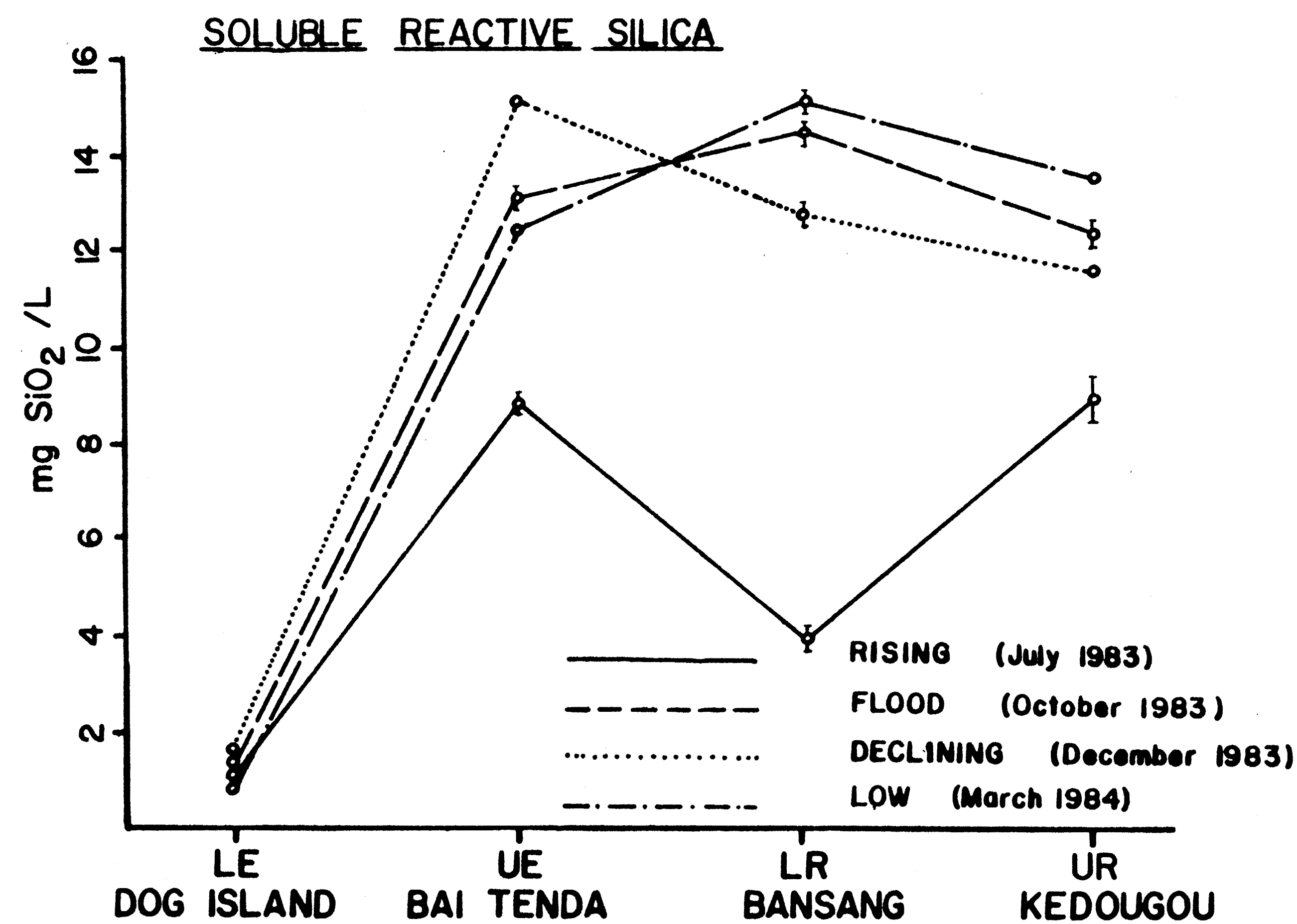

FIGURE 12. Mean soluble reactive silica concentrations and standard errors for each zone and season.

$m^3\ s^{-1}$). The loss rates for the catchment above Kedougou and Bansang were 1,780 and 475 kg $km^{-2}\ yr^{-1}$, respectively. The loss estimate for 1980-81 for the catchment above Bansang was 1,500 metric tons $km^{-2}\ yr^{-1}$ (Lesack et al. 1984). The 1983-84 calculations indicate that around nine times more SRS was being leached from the headwater catchment than the catchment in the lower portion of the continental subbasin.

The losses of soluble reactive silica from the river were from transport to the ocean and algal uptake. The levels observed during the July field trip partially reflected the reduction of this essential nutrient for algae growth during the long dry season. At this time the lowest observed values were found at all sampling sites except the lower estuary (Table 9).

The lower reaches of the Gambia River can be partitioned into different regions based on SRS concentrations and lateral location (Fig. 13). From Banjul, at the river mouth, to approximately 30 km upstream there existed throughout the year a region of constantly low SRS concentrations. The concentrations at this site were on average approximately an order of magnitude lower than in other locations in the river (Fig. 13). This region, which coincided with a low nitrate region and paralleled the marine-like lower estuary, was influenced by low SRS waters from the ocean. It encompassed the lower estuary sampling site which had an estimated yearly average concentration of 1.41 mg/L and observed concentrations ranging from 0.61 to 4.94 mg/L (Table 9). The relative variability of SRS was greater at this site but the magnitude of the fluctuation of SRS concentrations was smaller than the other sites. The low SRS region extended as far as 75 km upstream during the March sampling. This extension may have been due more to algal uptake than

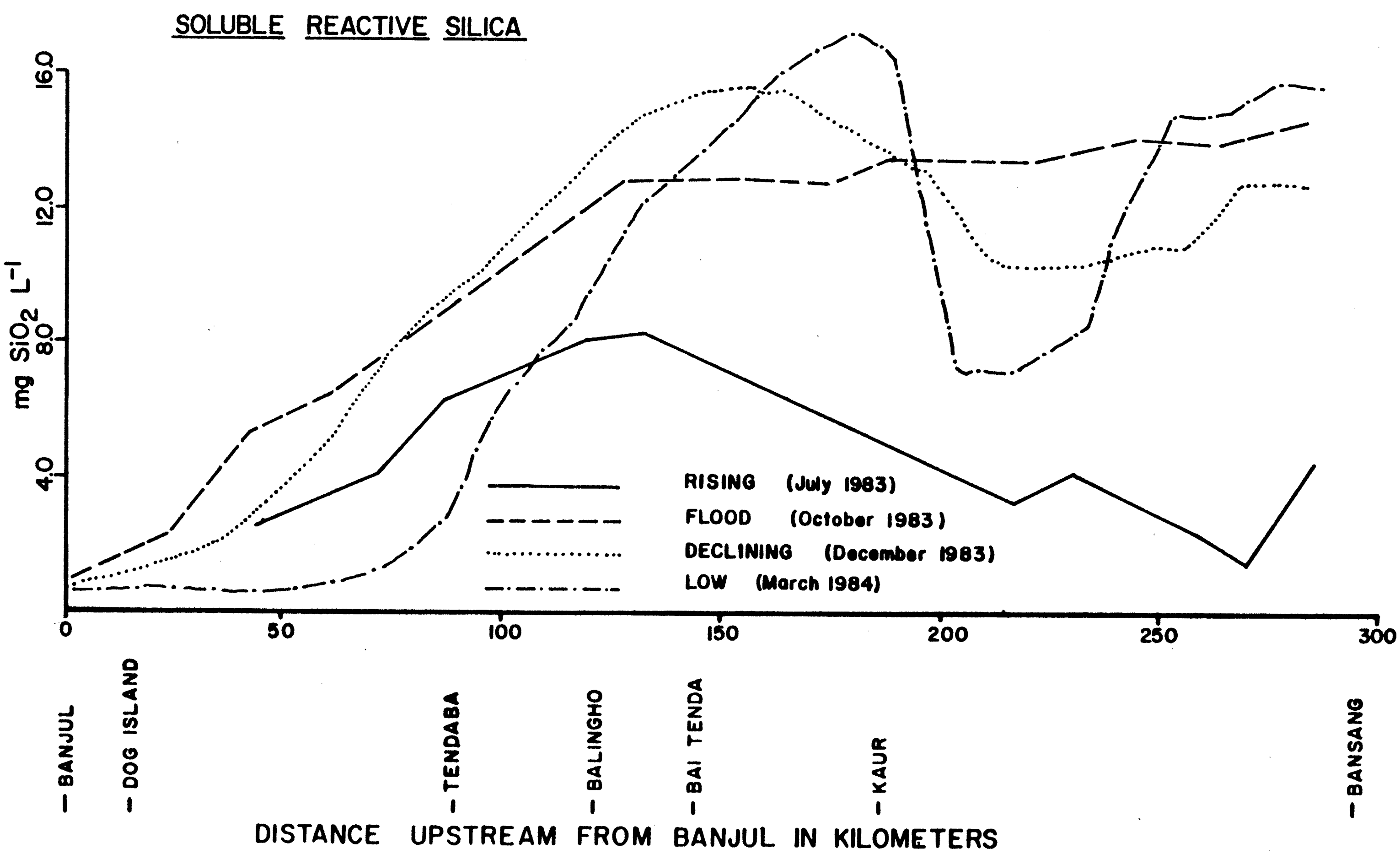

FIGURE 13. Distribution of soluble reactive silica by season in the lower 300 km of the Gambia River.

saltwater intrusion as indicated by a lower correlation of SRS with salinity than calculated for the flood and declining water stages.

Upstream from the lower estuary sampling site there existed an approximately 100-km segment of river which contained a gradient of steadily increasing SRS that followed the declining salt water gradient (Fig. 13). Throughout the year the SRS concentration in this segment was greatly influenced by the mixing of salt water and fresh water. There was a very significant correlation ($P<.01$) showing the inverse relationship between SRS and salinity for the samples taken from between sampling sites. A higher correlation was calculated for the flood and declining water samples than the other seasons. A region of generally higher concentrations and moderate seasonal variability existed from 125 to 200 km upstream. This region contained near its middle the upper estuary sampling site which had an estimated yearly average SRS concentration of 12.54 mg/L. Over the course of the four field trips the average concentration ranged from 8.79 to 15.4 mg/L (Table 9).

A segment of river that extended from Kaur to 75 km upriver contained slightly lower SRS concentrations during December than the segments bounding it (Fig. 13). This difference was very distinct during the March field trip. This same region had relatively low nitrate-nitrogen and high chlorophyll values compared to those taken in adjacent portions of the river.

The lower river sampling site at Bansang was located approximately 300 km upriver. This site was in a part of the river which was similar with regard to SRS to that surrounding the upper estuary site. The yearly estimated average SRS concentration was 11.68 mg/L and the observed average values ranged form 3.95 to 15.09 mg/L (Table 9). These data were very similar to the results presented by Lesack et al. (1984), who reported a range of values of

3.00 to 15.67 mg/L for samples taken in 1980-81. The estimated yearly average SRS concentration at Kedougou, the upper river sampling site, was 12.06 mg/L, which was similar to that found at the other sampling sites except the lower estuary. This similarity can also be seen in the range of 8.72 to 13.69 mg/L (Table 9).

Soluble reactive silica input to the river and transport down the river can be examined by following the SRS concentrations through the four field trips at all the sampling sites (Fig. 12). SRS increased between the rising and flood water field trips at all the sampling sites as a result of the addition of runoff high in leached silica. In the Gambia River this increase appeared to occur very abruptly. During the first field trip the SRS concentration more than doubled at the lower river zone from 2.4 to 4.8 mg/L within 24 hr. Also, following a rain event at the upper river site the SRS increased from 8.4 to 9.6 mg/L. Lesack et al. (1984), who sampled at Bansang during the flood stage, also found an abrupt increase in SRS with the appearance of runoff, but then the concentration changed very little with discharge. This observation was explained by a shorter residence time of runoff as discharge increased resulting in lower concentrations of leached SRS.

During the December and March field trip the SRS concentrations remained high at all sampling sites except for the lower estuary in March. One would expect a decline in SRS concentrations between March and July resulting from algal uptake. The decrease in SRS concentrations between the low water field trip and the rising water field trip cannot be explained in the freshwater areas by saltwater dilution, runoff, or ground water input. One explanation for these low values during the low flow period would be phytoplankton uptake. From the data collected between the primary sampling sites during the December

field trip and to an even greater extent during the March field trip there existed a region of greatly reduced SRS concentrations centered around Kudang. Chlorophyll determinations from these same samples indicated corresponding high concentrations of phytoplankton with high SRS concentrations. From these results one may assume that silica was being utilized by algae. This same general trend was also observed in samples collected at the lower river sampling site.

SOLUBLE REACTIVE PHOSPHORUS

The estimated yearly average soluble reactive phosphorus (SRP) concentration for the Gambia River was 9.2 μg P/L (mg/L) (Table 10). This value is low when compared to other unpolluted tropical rivers and also low when compared to commonly encountered values of 8-10 μg/L for natural waters (Meybeck 1982). The low SRP values reflect, among other things, small inputs from the sparsely populated state of the river basin as well as sanitation practices. SRP comprised 3% to 50% of the total phosphorus. The average percent for the study sites was: 41% for the lower estuary, 16% for the upper estuary, and 6% for the freshwater sites. The percent SRP of total phosphorus generally declined with increases in suspended matter. The percent SRP for the freshwater portions of the river were slightly higher than the norm for world rivers of 2% (Meybeck 1982). The greatly elevated percents in the estuary reflect the contribution of salt water which is high in SRP.

Observed values of SRP over the course of the study ranged from the limit of detection (.01 μg/L) in fresh water to 28.4 μg/L in the lower estuary (Table 10). Human activities have not greatly affected the levels of this key nutrient; this assumption arises from two facts: the watershed is not greatly developed and the observed levels are low. Spatial variability was high as a

TABLE 10. Soluble reactive phosphorus results (μg/L) from the Gambia River, 1983 and 1984.

Minimum

	Rising	Flood	Declining	Low	
Lower Estuary	20.65	13.84	17.63	14.14	13.84
Upper Estuary	2.80	2.17	.59	5.26	.59
Lower River	.73	.10	.35	.61	.10
Upper River	.01	.18	0.00	.25	.01
	.01	.10	.35	.25	.01

Maximum

	Rising	Flood	Declining	Low	
Lower Estuary	27.16	28.09	28.40	24.67	28.40
Upper Estuary	6.05	15.11	11.97	8.90	15.11
Lower River	3.00	3.84	2.84	2.77	3.84
Upper River	20.00	4.34	0.00	12.22	20.00
	27.16	28.09	28.40	24.67	28.40

Mean

	Rising	Flood	Declining	Low	
Lower Estuary	23.79	21.80	24.82	19.59	22.26
Upper Estuary	4.62	5.92	8.49	6.82	6.53
Lower River	1.54	1.98	1.33	1.70	1.65
Upper River	8.54	1.37	0.00	2.48	3.04
	7.57	8.92	11.52	8.54	9.22

Standard Deviation

	Rising	Flood	Declining	Low	
Lower Estuary	1.64	3.63	2.57	2.54	3.51
Upper Estuary	.88	1.77	1.93	.72	2.00
Lower River	.58	.63	.53	.45	.60
Upper River	8.47	.73	0.00	2.31	4.49
	8.46	8.83	9.99	7.59	8.84

Coefficient of Variation

	Rising	Flood	Declining	Low	
Lower Estuary	6.90	16.70	10.40	13.00	15.80
Upper Estuary	19.00	30.00	22.70	10.60	30.70
Lower River	37.30	31.50	40.10	26.70	36.40
Upper River	99.20	53.20	0.00	93.10	147.90
	111.80	99.00	86.70	88.80	95.90

result of seawater influence. The distribution of SRP in the Gambia River was highly correlated with seawater. The lower estuary zone, which is primarily an extension of the sea into the mouth of the Gambia River, had considerably higher SRP values than the other three zones. Contributions of SRP to the upper estuary from seawater were observed with saltwater intrusion at the study site in December (Fig. 14).

Seasonal variability was low for most of the river. The annual means for the four study sites were 22.3 μg/L for the lower estuary, 6.53 μg/L for the upper estuary, 1.65 μg/L for the lower river, and 3.04 μg/L for the upper river (Table 10). The distribution of SRP at the study sites during a field trip was quite variable; coefficients of variation often exceeded 20 percent (Table 10).

Longitudinal SRP variability, due mostly to salt water intrusion, was by far the single largest source of variation. Variability at the sampling sites due to location (Transect, station, depth) and tide collectively was sometimes greater than seasonal variability due to runoff, algal uptake, and saltwater intrusion.

The major sources of SRP were from saltwater intrusion and runoff. Inputs from runoff were evident from higher SRP values during high water stages at most of the sites. However, this was not as evident as for other nutrients. Anthropogenic loading was probably not a significant source. Communities along the Gambia River do not have sewer systems. Thus most human wastes do not reach the river except with freshwater runoff which is confined to only a few months of the year, and then the wastes are highly diluted. Thus, even though the lower river sampling site was only 2 km downstream from the village of Bansang, the lowest SRP concentrations in the entire river were

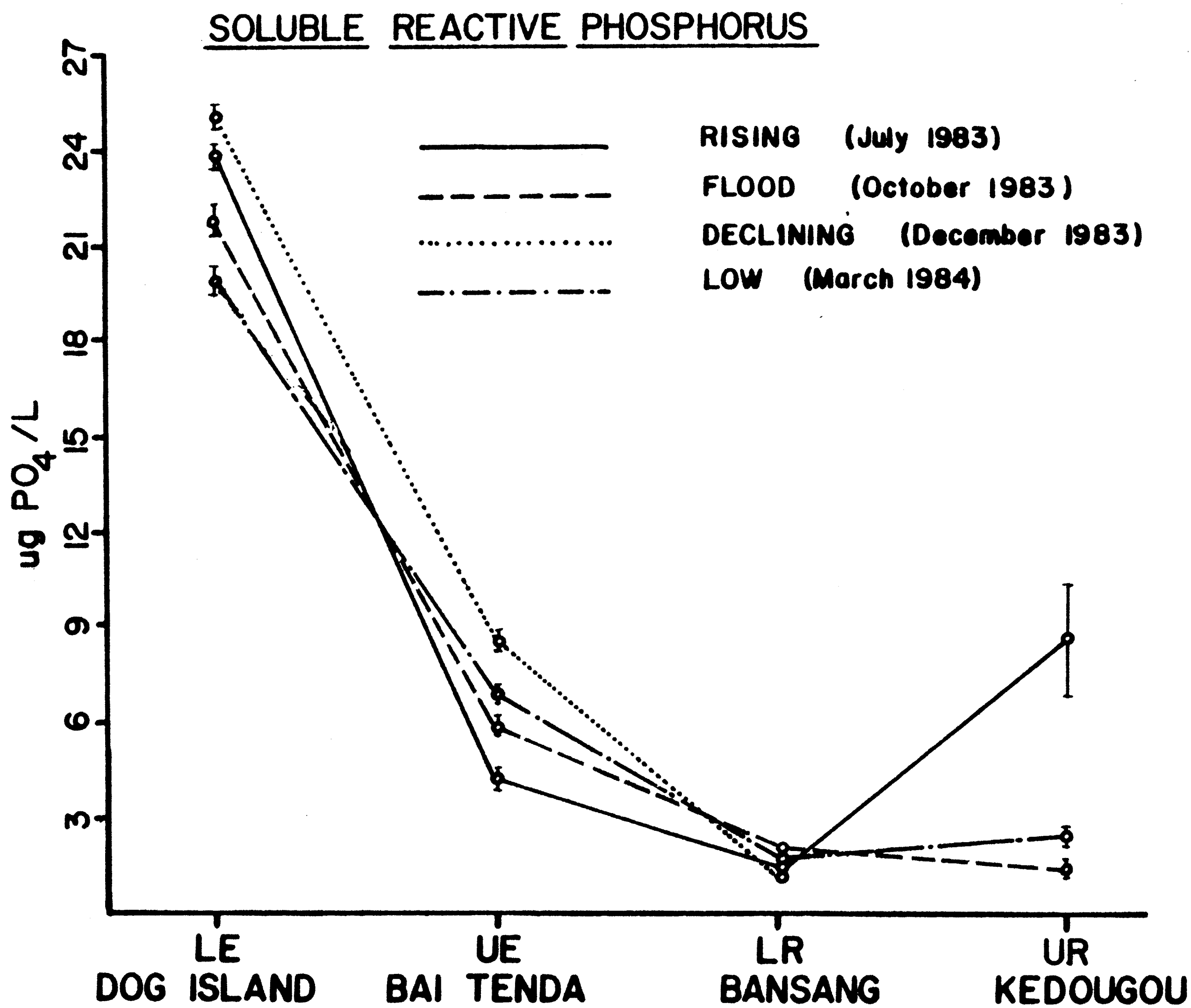

FIGURE 14. Mean soluble reactive phosphorus concentrations and standard errors for each zone and season.

found at this location. The high SRP concentrations observed at the lower estuary were primarily a function of high concentrations in sea water and not from anthropogenic activities.

The loading of SRP was estimated for Kedougou and Bansang to be 4,266 kg yr^{-1} and 3,351 kg yr^{-1}, respectively. The higher value reported for Kedougou may have been due to one very high value that greatly influenced these results. Total phosphorus loading is more meaningful than SRP due to the highly dynamic processes occurring within the framework of the phosphorus cycle. Because SRP concentrations in the river seldom exceeded the 5 μg/L value which is the average SRP concentration in unpolluted rain (Maybeck 1982), most likely there was no net contribution of SRP from the drainage basin.

The lower reaches of the Gambia River can be partitioned into regions based on SRP concentrations (Fig. 15). Throughout the study a region of very high SRP concentrations with high seasonal variability extended from the mouth of the river to approximately 100 km upriver from Banjul (Fig. 15). This region paralleled the lower estuary zone and extended into the upper estuary zone. In this region the SRP concentrations were greatly influenced by the high levels of SRP found in salt water. The lower estuary site, which was located in this region, had the highest yearly estimated average SRP concentration of all the sites (22.3 μg/L). Spatial variability at this site was high. Coefficients of variation ranged from 7-17% (Table 10).

Immediately upriver and adjacent to the region of very high SRP concentration existed a portion of the river which displayed high but steadily declining SRP values with distance upriver. In this region SRP values were moderately variable throughout the study. This SRP gradient followed the saltwater gradient almost to Bai Tenda (Fig. 15). Throughout the year, SRP in

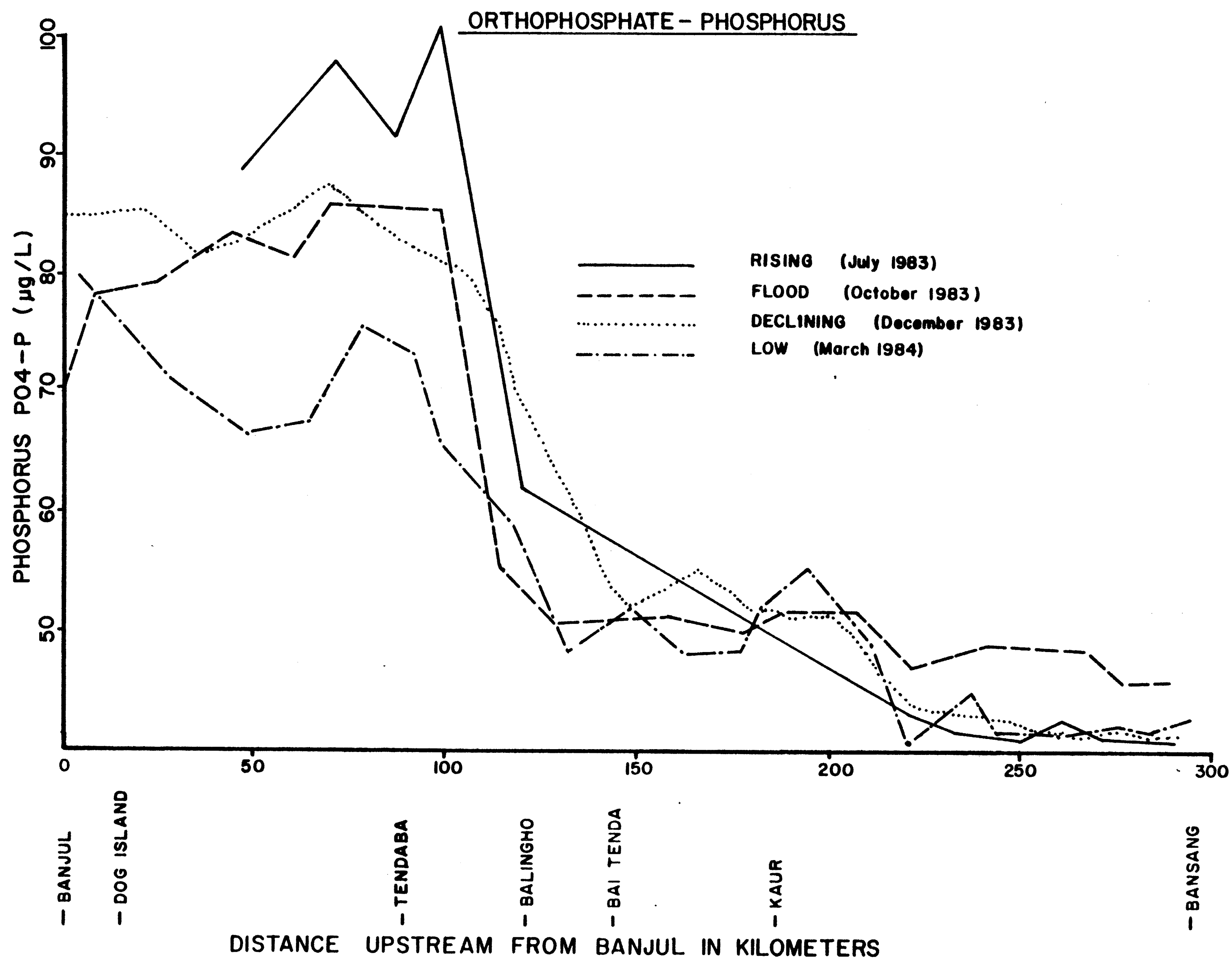

FIGURE 15. Distribution of soluble reactive phosphorus by season in the lower 300 km of the Gambia River.

this region was greatly influenced by the mixing of high SRP salt water and low SRP fresh water. Starting near Bai Tenda and extending approximately 225 km upriver existed a region of low SRP concentrations displaying moderate variability throughout the study. This region contained the upper estuary study site which had a yearly estimated SRP value of 6.53 μg/L. Spatial variability at this site was high and coefficients of variation ranged upward from 11% (Table 10). Extending farther upriver to the lower river site at Bansang was a region of very low annual variability. The lower river site had the lowest yearly estimated SRP concentration (1.65 μg/L) of any site, although its absolute variability was low (standard deviations from .45 to .63) due to the low values found there. Coefficients of variation ranged from 27 to 37 percent (Table 10).

The estimated annual average SRP concentration for Kedougou was 3.04 μg/L, a value that was greatly influenced by high concentrations during the annual flood. Throughout the rest of the year values were similar to the lower river site. Variability at this site was very high. Coefficients of variation ranged from 53-99% (Table 10). This may have been a reflection of the difficulty of processing and analyzing samples at the remote field sampling site.

SRP concentrations increased at lower river and upper estuary sites between the rising and flood waters field trips due to runoff. In contrast, SRP decreased between these two field trips at the upper river and lower estuary sampling sites. At the upper river site the decrease was because the analytical method used on the first field trip probably yielded higher values than the following trips, as well as become a pulse of SRP with runoff had already

occurred. The decrease in the lower estuary was most likely a result of dilution of the high SRP salt water by lower SRP runoff water.

Between the flood and declining water field trips, SRP in the estuarine zones increased most likely due to the intrusion of high SRP salt water. The lower river site showed a slight decrease during this same time span.

Between the declining water field trip in December and the low water field trip in march the freshwater discharge was very low; over 6 months had elapsed since storm flow inputs had entered the river. The absence of runoff served to reduce SRP concentrations in the freshwater portions of the river. However, in general the freshwater sites showed very small changes in SRP indicating that autochthonous sources maintained the SRP levels. Also, the uptake of SRP during this period could very likely be very low due to nitrogen limitation. Nitrate values were barely detectable. This is supported by the fact that chlorophyll values underwent little change during these months. In the estuary the decrease in SRP between the declining and low water field trips was attributed to algal and bacterial uptake. Most likely higher nitrate concentration that reached the lower estuary stimulated primary production, as seen in the 60% increase in chlorophyll values and elevated levels of ^{14}C uptake (Healey et al. 1985). Chlorophyll values increased 225% at the lower estuary site. With the reintroduction of high levels of salt water into the upper estuary zone one would expect an increase in SRP if it were not for algal uptake.

TOTAL PHOSPHORUS

The estimated yearly average total phosphorus (TP) concentration for the Gambia River was 43.2 μg P/L. Observed values over the course of the study ranged from 5.6 to 225 μg/L (Table 11). The estuarine zones generally had

TABLE 11. Total phosphorus results (μg/L) from the Gambia River, 1983 and 1984.

Minimum

	Rising	Flood	Declining	Low	
Lower Estuary	29.30	20.45	35.63	16.85	16.85
Upper Estuary	10.73	57.23	37.19	17.61	10.73
Lower River	23.71	18.44	22.68	5.61	5.61
Upper River	0.00	24.48	6.90	14.78	6.90
	10.73	18.44	6.90	5.61	5.61

Maximum

	Rising	Flood	Declining	Low	
Lower Estuary	155.21	86.64	125.18	215.88	215.88
Upper Estuary	51.60	100.18	224.98	93.10	224.98
Lower River	46.32	30.90	33.07	25.90	46.32
Upper River	0.00	79.81	149.48	90.92	149.48
	155.21	100.18	224.98	215.88	224.98

Mean

	Rising	Flood	Declining	Low	
Lower Estuary	46.42	43.47	53.93	109.84	58.20
Upper Estuary	19.93	72.98	75.55	34.56	49.90
Lower River	37.57	23.56	26.83	21.06	27.53
Upper River	0.00	51.17	15.56	26.39	31.71
	31.32	46.98	42.71	51.27	43.24

Standard Deviation

	Rising	Flood	Declining	Low	
Lower Estuary	24.76	11.94	20.74	47.35	35.84
Upper Estuary	6.74	7.81	39.84	15.75	30.80
Lower River	5.09	2.72	2.26	3.98	7.32
Upper River	0.00	18.98	26.43	18.57	26.97
	16.49	21.53	35.11	46.78	30.12

Coefficient of Variation

	Rising	Flood	Declining	Low	
Lower Estuary	53.30	27.50	38.50	43.10	61.60
Upper Estuary	33.80	10.70	52.70	45.60	61.70
Lower River	13.60	11.60	8.40	18.90	26.60
Upper River	0.00	37.10	169.80	70.30	85.10
	52.60	45.80	82.20	91.20	69.70

higher TP concentrations that the freshwater portion of the river. For the lower estuary this to a great extent was due to the high SRP concentrations in sea water. In the upper estuary this was most likely due to high concentrations of suspended material. TP minus SRP closely approximated particulate phosphorus. Over the course of the study the lower river zone had the lowest TP concentration of any zone. However, TP concentrations did not differ statistically between the lower and upper river zones throughout the study. The average TP concentration over the course of the study was 58.2 μg/L for the lower estuary, 49.9 μg/L for the upper estuary, 27.5 μg/L for the lower river, and 31.7 μg/L for the upper river (Table 11). Seasonal variability was lower for the freshwater zones than the estuary zones. The lower river was by far the most homogeneous, both spatially and temporally, of the zones. The standard deviations and coefficients of variation were high for the other zones both during a field trip and over the course of the study (Table 11). These results, especially those from the freshwater zones, were influenced to a degree by the fact that samples were not taken during the time of peak discharge. The TP concentrations in the Gambia River were affected to a greater degree by zone (location along the river), season (time of year), and discharge (streamflow) than by location at a sampling site (transect, station, depth) and tide.

The major source of total phosphorus was from runoff, thus its introduction from the catchment basin to the river was seasonal. The highest observed concentrations at the study sites were during the high water field trips (flood and declining), with the exception of the lower river and lower estuary.

At the lower river sampling site, most likely the peak TP concentrations resulting from storm runoff were not sampled because the peak streamflows occurred between the rising and flood water field trips (Fig. 16). This peak TP concentration could have been as much as 100 percent higher than the October mean value based on results from Lesack et al. (1984). They reported their highest values in August and September during the period of highest discharge. The increase in TP concentrations observed during the July field trip was associated with elevated streamflows (Fig. 16).

The high TP values observed in the lower estuary during the March sampling most likely resulted from a large quantity of sediment that was resuspended by spring tides. This phenomenon produced TP values that were four times higher than those observed in samples taken upstream from the lower estuary sampling site.

The TP loading was estimated for Kedougou to be 54,382 kg yr^{-1} and for Bansang 54,520 kg yr^{-1}. The loading results should be interpreted using the following considerations: 1) the estimates were calculated from only four field trips, and 2) rainfall in 1983-84 was very sparse. The Bansang estimate was around six times lower than that estimated by Lesack et al. (1984) of 325,000 kr yr^{-1} for 1980-81. The difference in the estimates can be partially explained by the 2.6 times larger discharge in 1980-81 as well as by the higher concentrations observed by Lesack et al. (1984). The loss rates for the catchments above Kedougou and Bansang were 7.20 kg km^{-2} yr^{-1} and 1.30 kg km^{-2} yr^{-1} respectively. The loss rate estimate for 1980-81 for the catchment above Bansang was 7.74 kg km^{-2} yr^{-1} (Lesack et al. 1984). The 1983-84 calculations indicated that almost all the loading came from the catchment above Kedougou. This could have well been the case because over 30% of the precipi-

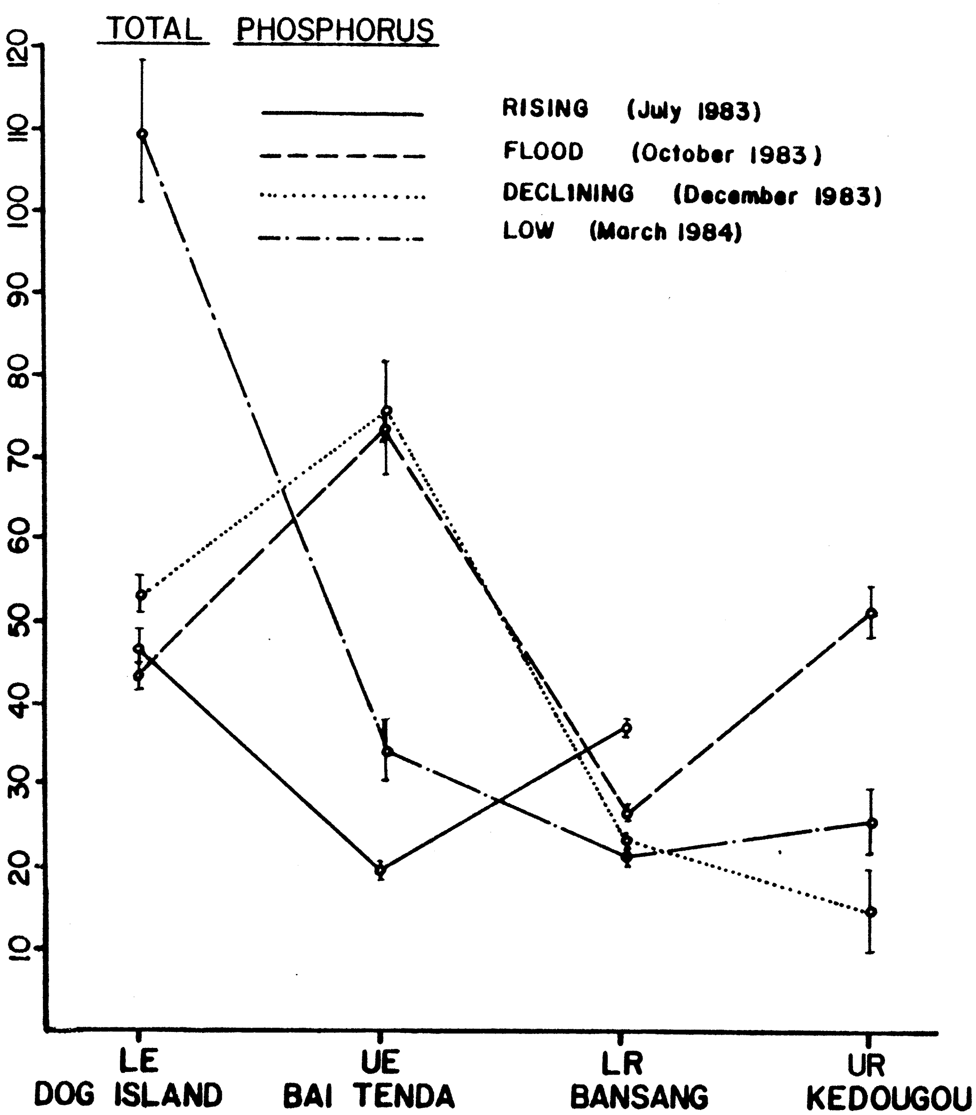

FIGURE 16. Mean total phosphorus concentrations and standard errors for each zone and season.

tation for the basin was in the headwaters area (Harza 1985). Also, in this region there are steeper gradients which contribute to higher rates of erosion. The losses of TP from the river were via transport to the ocean, sedimentation, and export to the ocean.

The lower reaches of the Gambia River can be roughly partitioned into regions based on TP concentrations (Fig. 17). This can be done by considering observed levels, seasonal variability, and longitudinal location. Throughout most of the year a region of slightly higher-than-average concentrations with low seasonal variability extended from the river mouth to approximately 30 km upstream (Fig. 17). This region encompassed the lower estuary sampling site which had an estimated yearly average TP concentration of 58.2 μg/L. The mean concentration for the field trips ranged from 43.5 μg/L in October to 109 μg/L in March. This region was characterized by fairly high standard deviations and coefficients of variation (Table 11).

Extending upriver from the lower estuary through the upper estuary regions almost to the lower river sampling site at Bansang was a segment of the river that displayed a high degree of seasonal and longitudinal variability. An area of high TP concentrations was associated with this segment (Fig. 17). This region, containing the upper estuary sampling site, had an estimated yearly average TP concentration of 49.9 μg/L. The mean concentrations for the field trips ranged from 19.9 μg/L in July to 75.6 μg/L in December (Table 11). Standard deviations and coefficients of variation were similar to those found in the lower estuary. Movement of the high TP areas for the most part preceded saltwater intrusion. During the December and March field trips, high TP concentrations were found just upriver from the saltwater-freshwater interface. On almost all the field trips, the high TP areas coincided exactly with

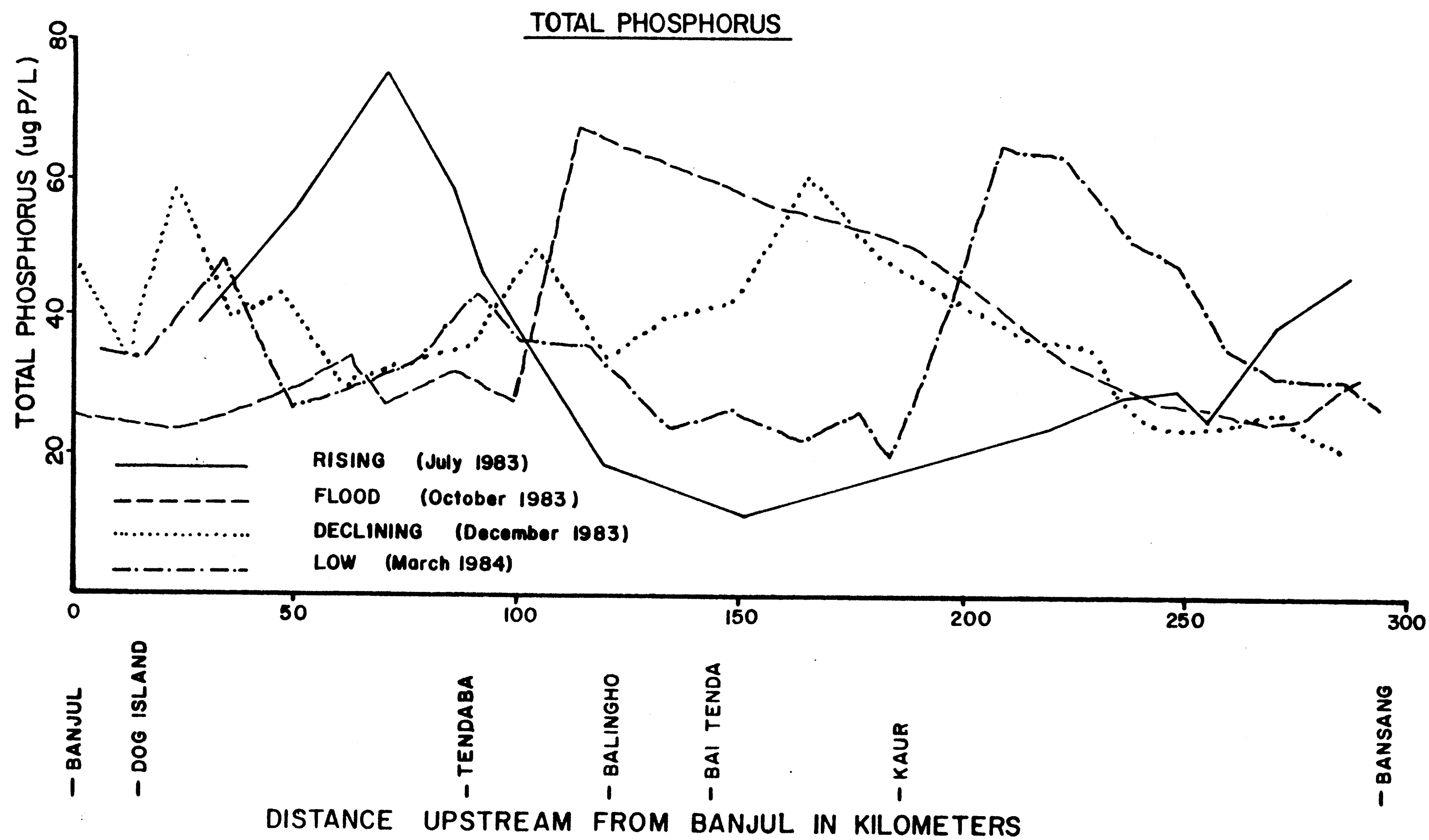

FIGURE 17. Distribution of total phosphorus by season in the lower 300 km of the Gambia River.

suspended solids peaks. This implies that a large contribution of the TP in these areas came from particulate matter. This is supported by the high correlation between suspended solids and TP from both between as well as at the study sites. This would be expected because particulate phosphorus (PP) represents about 95% of the phosphorus carried by rivers (Meybeck 1982).

Lesack et al. (1984) observed that PP comprised about 38% of the TP in samples taken at Bansang. At Bansang, the estimated yearly average TP concentration from the Gambia River Basin Study was 27.5 μg/L. Here the TP concentrations were fairly constant throughout the study. They ranged from 21.0 μg/L in March to 37.6 μg/L in July (Table 11). This was very similar to the range reported by Lesack et al. (1984) of from 29 μg/L to 48 μg/L excluding the months of August (77 μg/L) and September (81 μg/L). This sampling site was the most homogeneous of all sampling sites with regard to TP concentrations, standard deviations, and coefficients of variation (Table 11).

At Kedougou, the estimated yearly average TP concentration was 31.7 μg/L. The mean TP concentrations ranged from 51.2 μg/L during high streamflows in October to 15.6 μg/L in December. The standard deviations and coefficients of variation were large for the Bansang samples (Table 11).

TP input to the river and transport down the river can be examined by following TP concentrations through the field trips at the sampling sites (Fig. 16). The highest TP concentrations in the freshwater portion of the river most likely occurred when peak streamflows in September and October were transported down the river. By the time of the October field trip the initial runoff contribution of TP had most likely passed the lower river sampling site (Fig. 17). During the October sampling, TP concentrations at Kedougou were high but probably beginning to decline from the most elevated levels. By

December, the TP concentrations reached a low flow level of 20 µg/L which was maintained throughout the rest of the study.

At Bansang during the October field trip the average TP level of 23.6 µg/L was lower than the July values. This TP level was relatively consistent throughout the study.

At Bai Tenda the highest TP concentrations were measured during the October and December field trips (average value of 73.0 and 75.6 µg/L, respectively) and was maintained through the December field trip. By March a TP value of 34.6 µg/L was observed, declining toward the July level of 19.9 µg/L which existed prior to storm flood concentrations.

At Dog Island the storm flow elevation of TP was not observed until the December field trip. Then the level was elevated from prestorm conditions (average, 44.4 µg/L) to 53.9 µg/L (Table 11). The high March TP level resulted from a strong spring tide as discussed above.

TOTAL NITROGEN

The estimated yearly average total nitrogen (TN) concentration for the Gambia River was 296 µg/L (Table 12). Observed values over the course of the study ranged over two orders of magnitude from 5 to 905 µg/L (Table 12). Similar to total phosphorus, the estuarine zones generally had higher TN concentrations than the freshwater zones. Compared to the other zones, concentrations were lowest in the lower river zone. Mean TN concentrations from each field trip were highly variable among the four study sites. Standard deviations and coefficients of variation for samples taken at the study sites during a field trip were always high. Coefficients of variation were from 10 to 44 percent (Table 12). Seasonal variability was very high in all the zones and slightly higher in the freshwater zones. The TN concentrations in the

TABLE 12. Total nitrogen results ($\mu g/L$) from the Gambia River, 1983 and 1984.

Minimum

	Rising	Flood	Declining	Low	
Lower Estuary	165.01	187.72	192.13	288.44	165.01
Upper Estuary	117.65	327.56	192.06	138.72	117.65
Lower River	114.15	143.48	5.13	47.66	5.13
Upper River	0.00	182.66	86.03	174.77	86.03
	114.15	143.48	5.13	47.66	5.13

Maximum

	Rising	Flood	Declining	Low	
Lower Estuary	533.04	495.08	467.68	904.59	904.59
Upper Estuary	464.90	557.25	398.97	527.06	557.25
Lower River	633.25	282.73	162.08	205.74	633.25
Upper River	0.00	785.57	208.64	516.36	785.57
	633.25	785.57	467.68	904.59	904.59

Mean

	Rising	Flood	Declining	Low	
Lower Estuary	249.43	325.68	342.26	499.96	347.70
Upper Estuary	279.70	461.95	248.68	290.18	341.88
Lower River	356.29	206.17	93.71	120.76	216.57
Upper River	0.00	403.60	116.19	236.49	254.32
	299.93	338.51	199.64	296.72	295.86

Standard Deviation

	Rising	Flood	Declining	Low	
Lower Estuary	87.40	53.46	81.54	150.70	118.85
Upper Estuary	78.85	49.77	47.28	84.91	112.27
Lower River	89.49	22.90	41.34	32.53	110.18
Upper River	0.00	162.27	29.08	74.45	165.66
	93.83	121.81	113.50	174.29	134.68

Coefficient of Variation

	Rising	Flood	Declining	Low	
Lower Estuary	35.00	16.40	23.80	30.10	34.20
Upper Estuary	28.20	10.80	19.00	29.30	32.80
Lower River	25.10	11.10	44.10	26.90	50.90
Upper River	0.00	40.20	25.00	31.50	65.10
	31.30	36.00	56.90	58.70	45.50

Gambia River were influenced to a greater degree by zone (location along the river), season (time of year), and discharge (streamflow) than by location at a sampling site (transect, station, depth) and tide.

The major source of TN was from runoff, hence its introduction from the catchment basin to the river was seasonal (Fig. 18). The results were similar to total phosphorus. The highest values occurred during the high water stages (flood and declining), with the exception of the lower river and the lower estuary which can be explained using the same logic as for the total phosphorus anomalies.

The loading of TN was estimated at Kedougou to be 433,360 kg yr^{-1} and at Bansang 473,630 kg yr^{-1}. These loading results should be interpreted using the same considerations as for total phosphorus. The Bansang estimate was over 100 times lower than the estimate by Lesack et al. (1984) of 53,000,000 kg yr^{-1} for 1980-81. The discrepancy can partially explained by the 2.5 times lower rainfall in 1983-84 and partially by the elevated values observed by Lesack et al. (1984), predominantly during peak loadings. The loss rates for the catchments above Kedougou and Bansang were 57.4 and 11.3 kg km^{-2} yr^{-1} respectively. The loss rate estimate for 1980-81 was 116 kg km^{-2} yr^{-1}. The loss rate calculations indicated that almost all the loading came from the catchment above Kedougou. This could have well been the case because over 30% of the precipitation for the region fell in the headwater portion of the continental subbasin. The loss of TN from the river was via transport to the ocean and sedimentation.

The lower reaches of the Gambia River, for the purpose of this discussion, were partitioned into regions which encompass the study sites (Fig. 19). These regions were even more poorly defined than those used for total phospho-

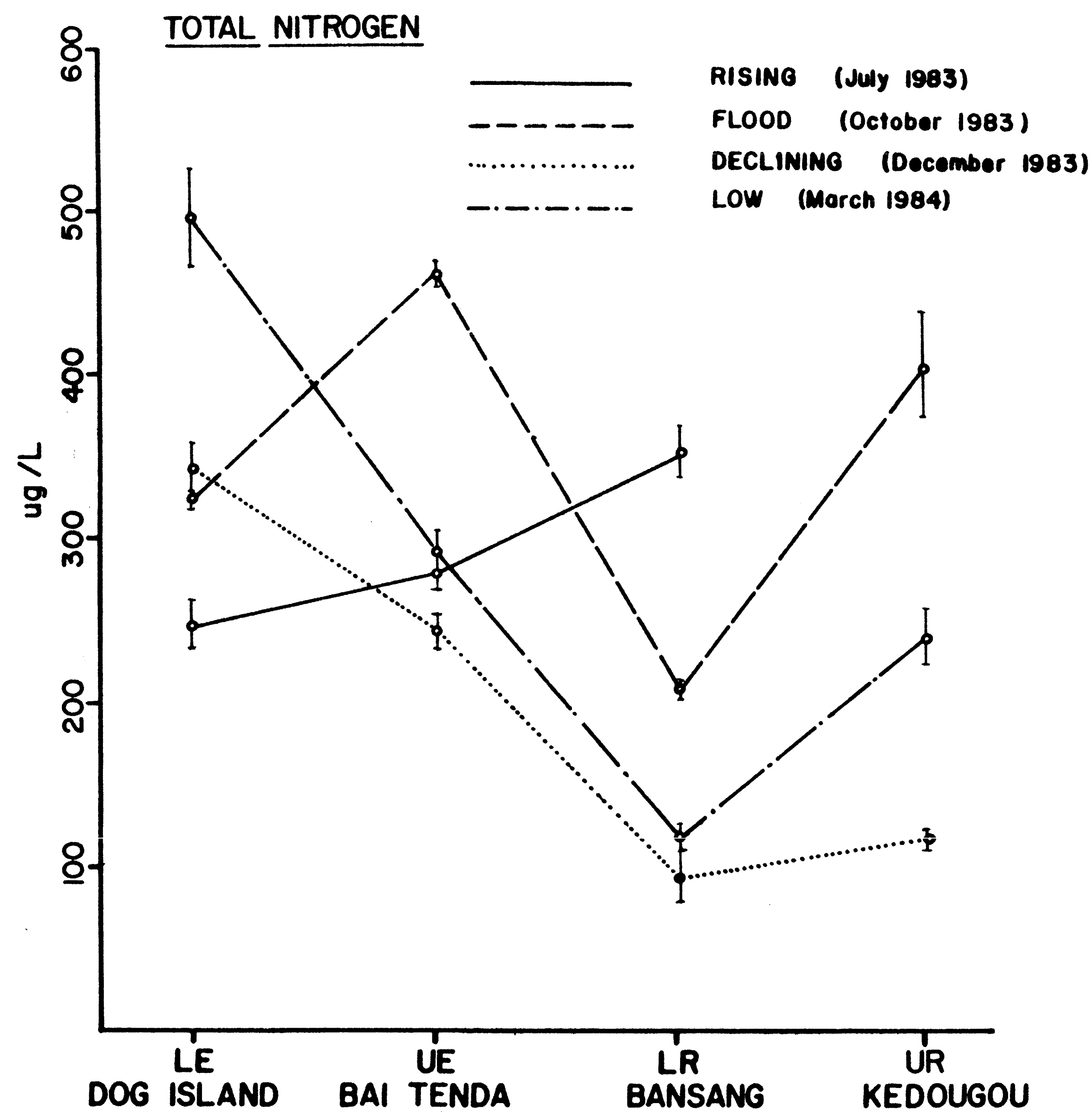

FIGURE 18. Mean total nitrogen concentrations and standard errors for each zone and season.

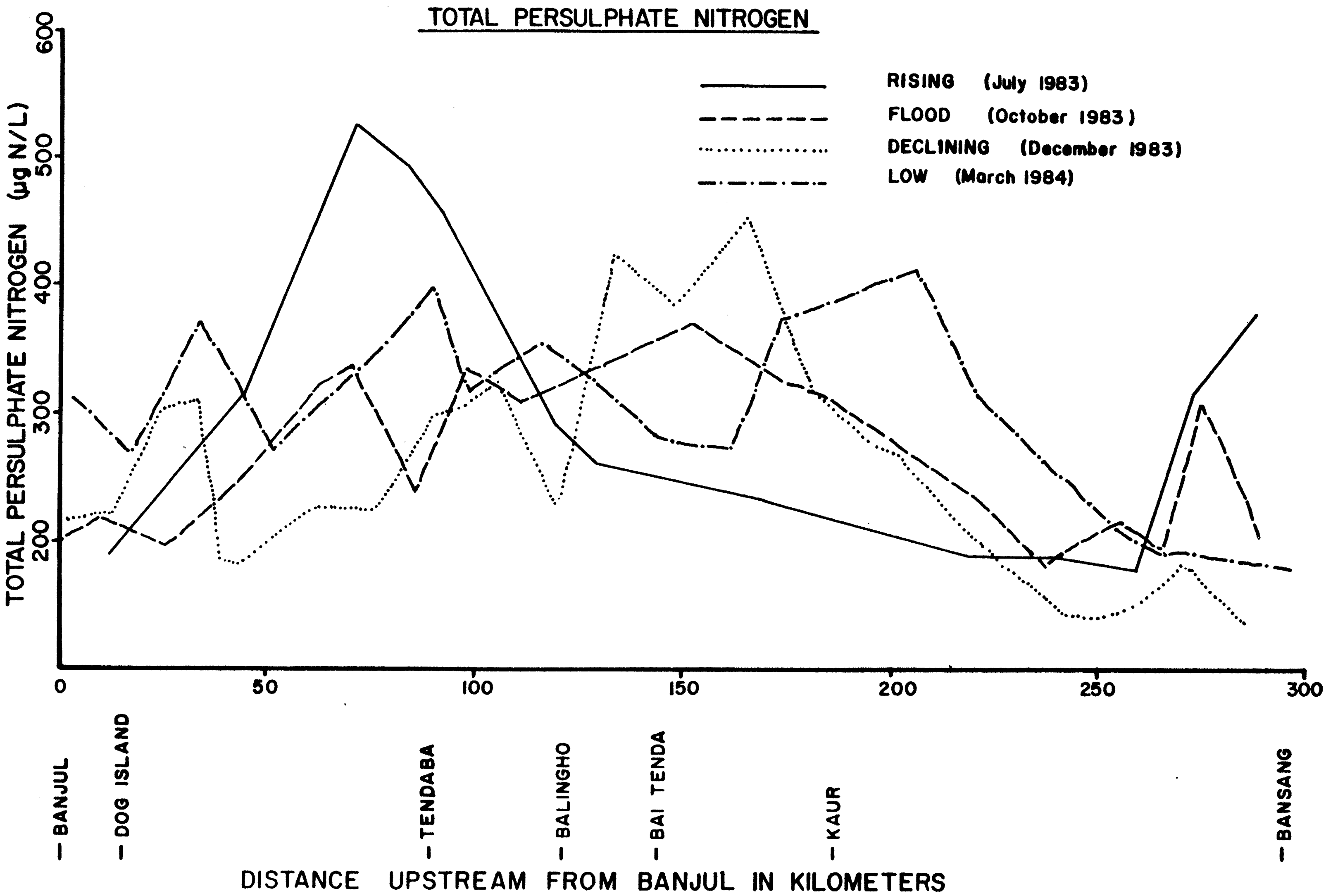

FIGURE 19. Distribution of total nitrogen by season in the lower 300 km of the Gambia River.

rus because longitudinal and spatial variability of TN was great throughout the entire river. The interpretation of TN data is difficult, as is the case for total phosphorus, because of the many forms which are oxidized to analite. The nitrate component, as mentioned earlier, is the major dissolved inorganic species. The difference between TN and nitrate yields a value which reasonably approximates the organic nitrogen component. This contains both a dissolved and particulate fraction which is the dominant form in river suspended material (Meybeck 1982).

The lower estuary site had the highest yearly estimated average TN value of all the zones (348 μg/L) (Table 12). Exclusion of the March value, which is probably not very representative due to extremely high suspended solids loads, reduces the annual estimate to 302 μg/L. The mean values from the field trips ranged from 249 μg/L in July to 500 μg/L in March. On average, 92 percent of the TN in the lower estuary site was organic. This ratio changed very little throughout the study. Seasonal variability of TN was generally very low at this site. The range of mean values was 93 μg/L excluding the March data. Inclusion of the March data expands the range of means to 250 μg/L.

TN at the upper estuary site had a yearly estimated average value of 342 μg/L, which was close to the estimate for the lower estuary. The mean values from the four field trips ranged from 462 μg/L in October to 249 μg/L in December (Table 12). On average, 58% of the TN in the upper estuary was organic. This ranged from 18% in December to 85% in March. The nitrate component was very large during high water stages. The seasonal variability in the upper estuary was relatively large and similar to the sites farther upstream.

The lower river site had the lowest yearly estimated average TN (217 μg/L) of all the sites (Table 12). The true value may be slightly higher because samples were not taken during peak TN loadings. This can be illustrated by calculations using the data of Lesack et al. (1984). The estimated yearly average for 1980-81 was 755 μg/L. If the peak TN loading month was excluded, this average would drop to 692 μg/L. If the same 4 months were used to compute the annual average TN, as were in the Gambia River Basin Study, the estimate would be 644 μg/L or 15% lower. The mean values for the field trips ranged from 356 μg/L in July to 94 μg/L in December, which was the lowest observed mean for the study (Table 12). Lesack et al. (1984) observed much higher values. They reported values ranging from 1,810 μg/L in September to 242 μg/L in December. On the average, 83% of the TN in the lower river was organic. This ranged from 55% in October to 100% in March.

TN at the upper river site had a yearly estimated average value of 254 μg/L. The mean values for the field trips ranged from 404 μg/L in October to 116 μg/L in December (Table 12). On the average, 99% of the upper river TN was organic.

Total nitrogen input to the river and transport downstream was examined at several sampling sites. Similar to total phosphorus, the highest TN concentrations in the freshwater portions of the river most likely occurred in September and had been transported down river by the October sampling. The overall trends were similar to total phosphorus.

At Kedougou, during October, TN concentrations reached the highest observed value of 404 μg/L as a result of runoff. By December the mean value had declined around four-fold. There was a slight increase by March.

At Bansang, during October, TN levels were lower than July. The July levels may have been elevated due to the initial effects of storm flow. TN followed the same pattern here as at Kedougou with the lowest observed value in December and a slight increase in March. The upper estuary displayed the same seasonal trend as at Kedougou. In the lower estuary, TN slowly increased to a maximum in December. High TN concentrations persisted into March, most likely resulting from resuspension due to strong spring tidal currents as discussed above.

DISSOLVED OXYGEN

In most regions of the Gambia River the per cent saturation of dissolved oxygen (DO) was maintained throughout the study at or above an average of 80% (Table 13). Dissolved oxygen was present in every sample that was analyzed. The observed values ranged from 32 to 133% saturation. The mean DO values observed at the sampling sites over the course of the study in mg/L and percent saturation were 5.9 and 86.6% for the lower estuary, 4.8 and 59.3% for the upper estuary, 7.0 and 87.1% for the lower river, and 7.7 and 97.9% for the upper river. When compared to the other regions, the upper estuary zone consistently displayed lower DO levels. Here the mean DO ranged from 50 to 75%. The shallow, faster-flowing upper river waters were well oxygenated and usually displayed the highest mean DO values.

Spatial variability among zones of the river was usually greater than seasonal variability and always greater than the variability within one zone during a field trip. The low DO values observed at the upper estuary site made a major contribution to spatial variability. Throughout the course of the field studies the mean DO in the lower estuary changed relatively little compared to the other zones. In contrast an area of great seasonal change was

TABLE 13. Dissolved oxygen (percent saturation) results from the Gambia River, 1983 and 1984.

	Rising	Flood	Declining	Low	
			Minimum		
Lower Estuary	83.20	62.40	38.00	32.50	32.50
Upper Estuary	58.00	50.90	43.10	56.70	43.10
Lower River	72.00	79.00	85.20	93.10	72.00
Upper River	86.00	87.60	84.00	69.70	69.70
	58.00	50.90	38.00	32.50	32.50
			Maximum		
Lower Estuary	108.30	121.80	102.30	98.10	121.80
Upper Estuary	75.80	69.30	59.80	81.20	81.20
Lower River	92.10	91.40	94.70	103.60	103.60
Upper River	133.00	95.00	111.00	91.90	133.00
	133.00	121.80	111.00	103.60	133.00
			Mean		
Lower Estuary	93.46	84.27	86.74	86.21	86.65
Upper Estuary	65.49	56.41	50.36	74.68	59.27
Lower River	79.54	87.88	89.23	96.50	87.06
Upper River	113.70	92.32	98.00	80.56	97.90
	80.64	77.19	78.03	85.40	79.71
			Standard Deviation		
Lower Estuary	6.79	8.58	12.22	9.49	10.17
Upper Estuary	5.50	3.09	4.70	5.16	9.32
Lower River	4.75	1.68	2.56	2.73	6.14
Upper River	12.78	2.33	6.94	6.48	13.99
	16.78	15.11	19.78	10.30	16.61
			Coefficient of Variation		
Lower Estuary	7.30	10.20	14.10	11.00	11.70
Upper Estuary	8.40	5.50	9.30	6.90	15.70
Lower River	6.00	1.90	2.90	2.80	7.10
Upper River	11.20	2.50	7.10	8.00	14.30
	20.80	19.60	25.30	12.10	20.80

the upper estuary (Table 13 and Fig. 20). Sampling variability at the sites during a field trip was moderate to low. Coefficients of variation were often less than 10% (Table 13).

The upper estuary zone included a region of consistently low DO in comparison to the rest of the river (Fig. 21). This region of low DO roughly extended from Tendaba to Kaur with the lowest values occurring near the upper estuary sampling site at Bai Tenda. Reduced DO saturation in this region was most pronounced during the high water stages. During the low water field trip reduced oxygen concentrations were observed further up river to roughly between Balingho and Baboon Islands. The low DO values found in the upper estuary may have resulted from oxygen consumption by decomposition and denitrification (Twilley 1985) if suspended solids in this region during the high water stages and/or lower primary production due to the suspended solids reduction of light. Respiration on the tidal flood plains found in this area may also have contributed to the low DO values. In most cases DO values declined following the introduction of allochthonous materials to the river in runoff. This was particularly true when high levels of suspended solids were observed.

ALKALINITY

The major component in alkalinity was carbonate ions because the pH of Gambia River water never exceeded 8.08. Silicates in fresh water played a minor role in alkalinity, as did borates and phosphates in salt water. Bicarbonate is by far the major anion and major solute in the dilute solution of the Gambia River water. Bicarbonate and silicate together constitute 75% of the solutes by weight (Lesack et al. 1984).

The estimated yearly average total alkalinity concentration for the Gambia River was 57.2 mg $CaCO_3$/L, while for the freshwater portions of the river

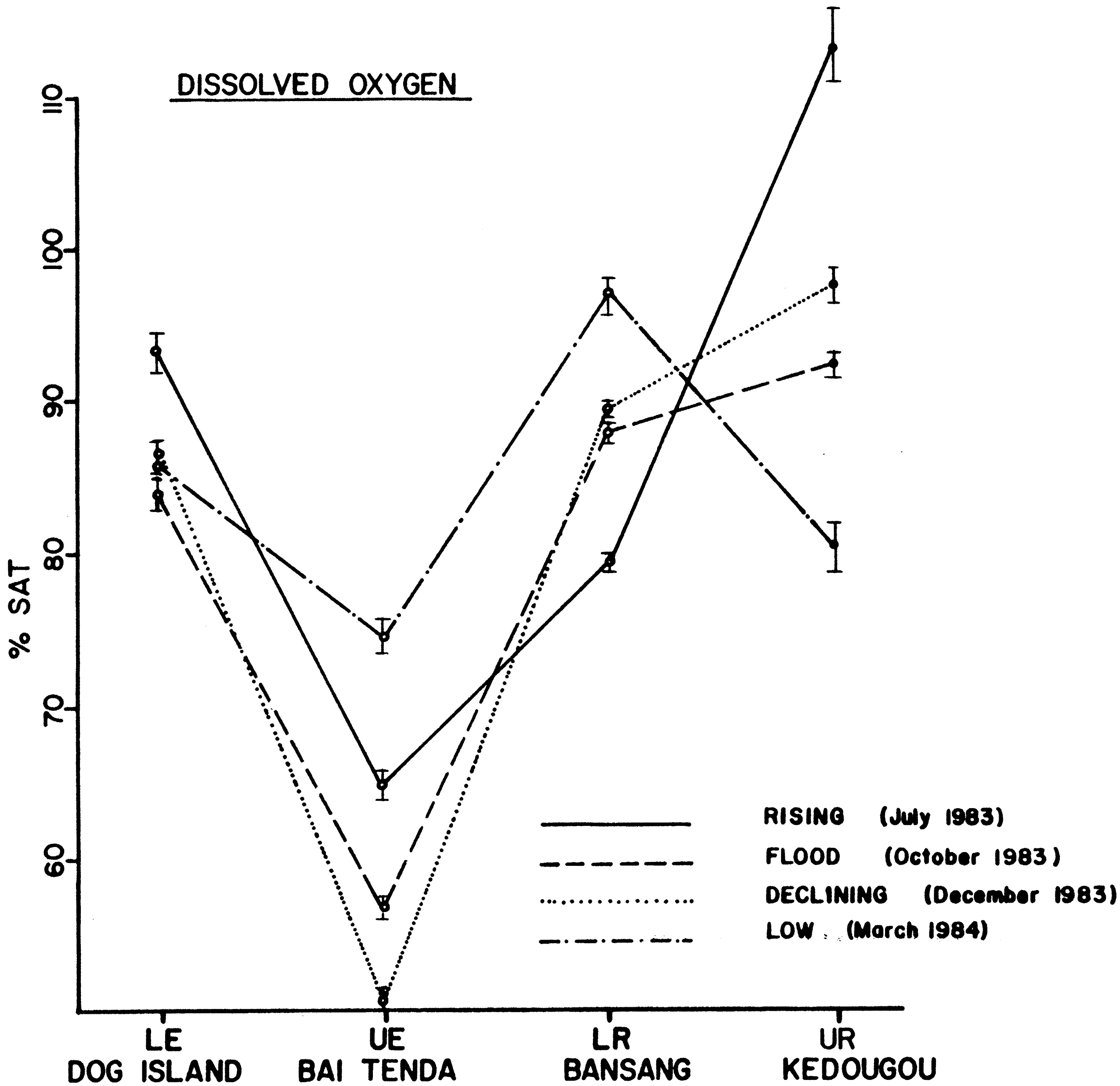

FIGURE 20. Mean dissolved oxygen levels (percent saturation) for each zone and season.

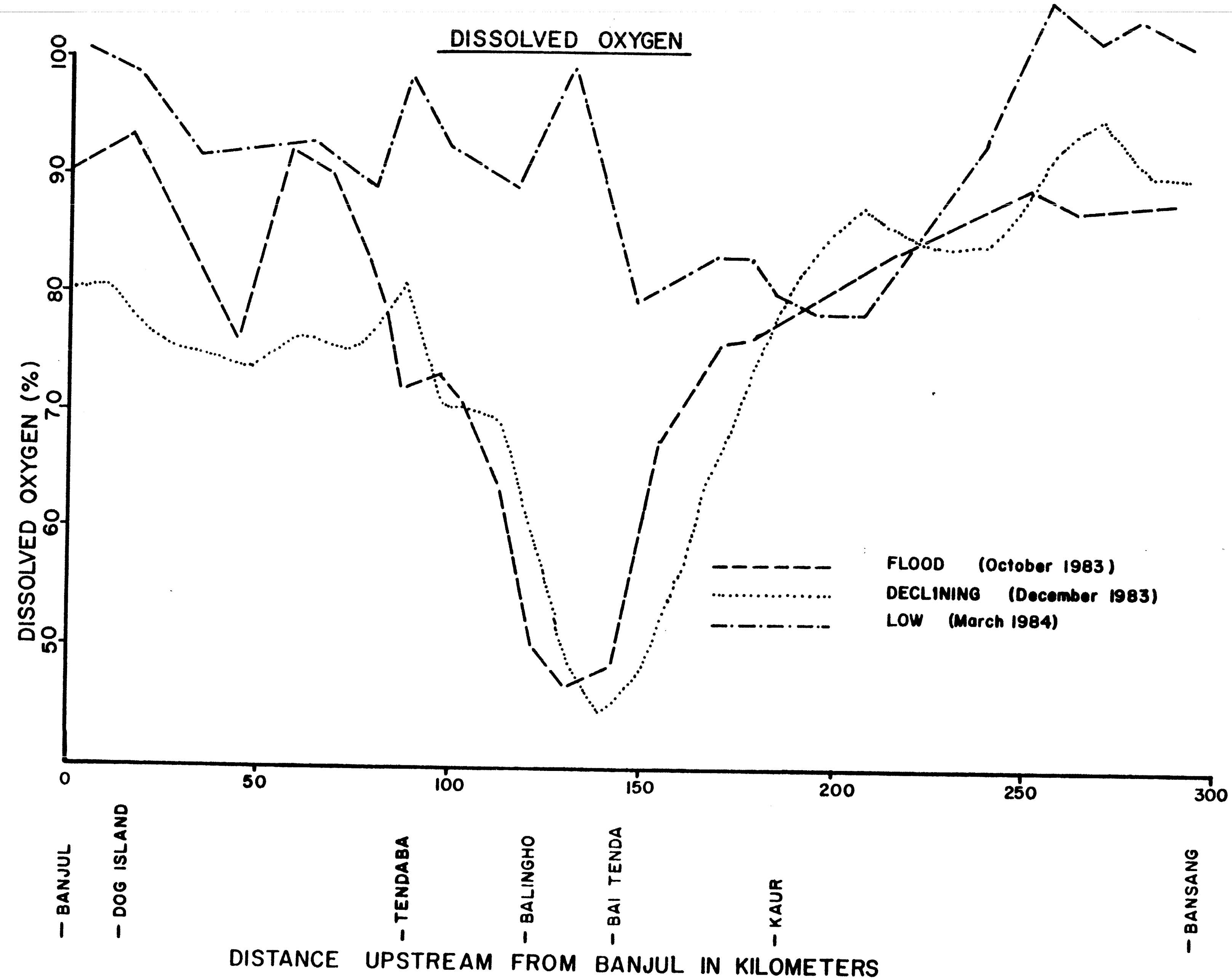

FIGURE 21. Distribution of dissolved oxygen by season in the lower 300 km of the Gambia River.

it was 24.7 mg $CaCO_3$/L. The low alkalinity of the Gambia River reflects the lithology of the region. The major source of alkalinity for the freshwater portions was probably ground water. Discharge had a dilution effect on alkalinity. Observed alkalinity values over the course of the study ranged from 15.2 to 120.8 mg $CaCO_3$/L (Table 14). The lower estuary zone had approximately twice the alkalinity of the upper estuary zone which was approximately twice as high as the freshwater zones. The higher alkalinity in the estuary zones was due to salt water. The average total alkalinity concentrations over the course of the study were 109.0 mg $CaCO_3$/L for the lower estuary, 55.1 mg $CaCO_3$/L for the upper estuary, 25.2 mg $CaCO_3$/L for the lower river, and 24.3 mg $CaCO_3$/L for the upper river.

Seasonal variability was very low in the lower estuary, high in the upper estuary, and intermediate in the freshwater zones (Table 14). The range of means was 12.0, 45.6, 16.0, and 21.4 mg $CaCO_3$/L for the lower estuary, upper estuary, lower river, and upper river, respectively. Longitudinal variability in alkalinity in the Gambia River was large because of the presence of sea water (Fig. 22). Variability at one site during one field trip was low. Standard deviations never exceeded 3.0 mg $CaCO_3$/L and coefficients of variation never exceeded 9.0% (Table 14). The alkalinity concentrations in the Gambia River were influenced to a far greater degree by zone (location along the river) resulting from variations in salinity than by season (time of year) as a result of dilution by runoff with increased discharge and by location at the sampling site (transect, station, and depth) and tide.

Ground water, which was about 3 to 13 times higher in bicarbonate than fresh water, probably was the major source of alkalinity in the freshwater zones. This can be seen by the elevated values in March and to a greater ex-

TABLE 14. Alkalinity results (mg/L) from the Gambia River, 1983 and 1984.

Minimum

	Rising	Flood	Declining	Low	
Lower Estuary	110.70	100.00	104.20	111.60	86.80
Upper Estuary	67.00	21.55	46.50	67.30	21.55
Lower River	34.75	17.50	20.50	23.85	17.50
Upper River	34.00	15.75	15.33	21.25	15.33
	34.00	15.75	15.33	21.25	15.23

Maximum

	Rising	Flood	Declining	Low	
Lower Estuary	113.50	106.70	109.40	120.80	120.80
Upper Estuary	75.00	30.35	56.50	78.20	78.20
Lower River	38.25	22.10	21.75	24.50	38.25
Upper River	45.00	21.25	22.33	24.50	45.00
	113.50	106.70	109.40	120.80	120.80

Mean

	Rising	Flood	Declining	Low	
Lower Estuary	112.18	103.31	107.08	115.36	108.95
Upper Estuary	71.10	27.06	51.20	72.67	55.11
Lower River	36.19	20.20	21.23	24.25	25.21
Upper River	40.12	18.68	18.73	22.49	24.34
	61.39	46.79	54.54	67.74	57.22

Standard Deviation

	Rising	Flood	Declining	Low	
Lower Estuary	.67	1.23	1.08	1.79	5.24
Upper Estuary	1.78	1.38	2.60	2.32	18.69
Lower River	.68	1.09	.24	.11	6.26
Upper River	2.11	1.65	1.17	.81	9.03
	27.11	36.99	35.81	37.99	36.01

Coefficient of Variation

	Rising	Flood	Declining	Low	
Lower Estuary	.60	1.20	1.00	1.60	4.80
Upper Estuary	2.50	5.10	5.10	3.20	33.90
Lower River	1.90	5.40	1.20	.50	24.80
Upper River	5.30	8.80	6.20	3.60	37.10
	44.20	79.10	65.70	56.10	62.90

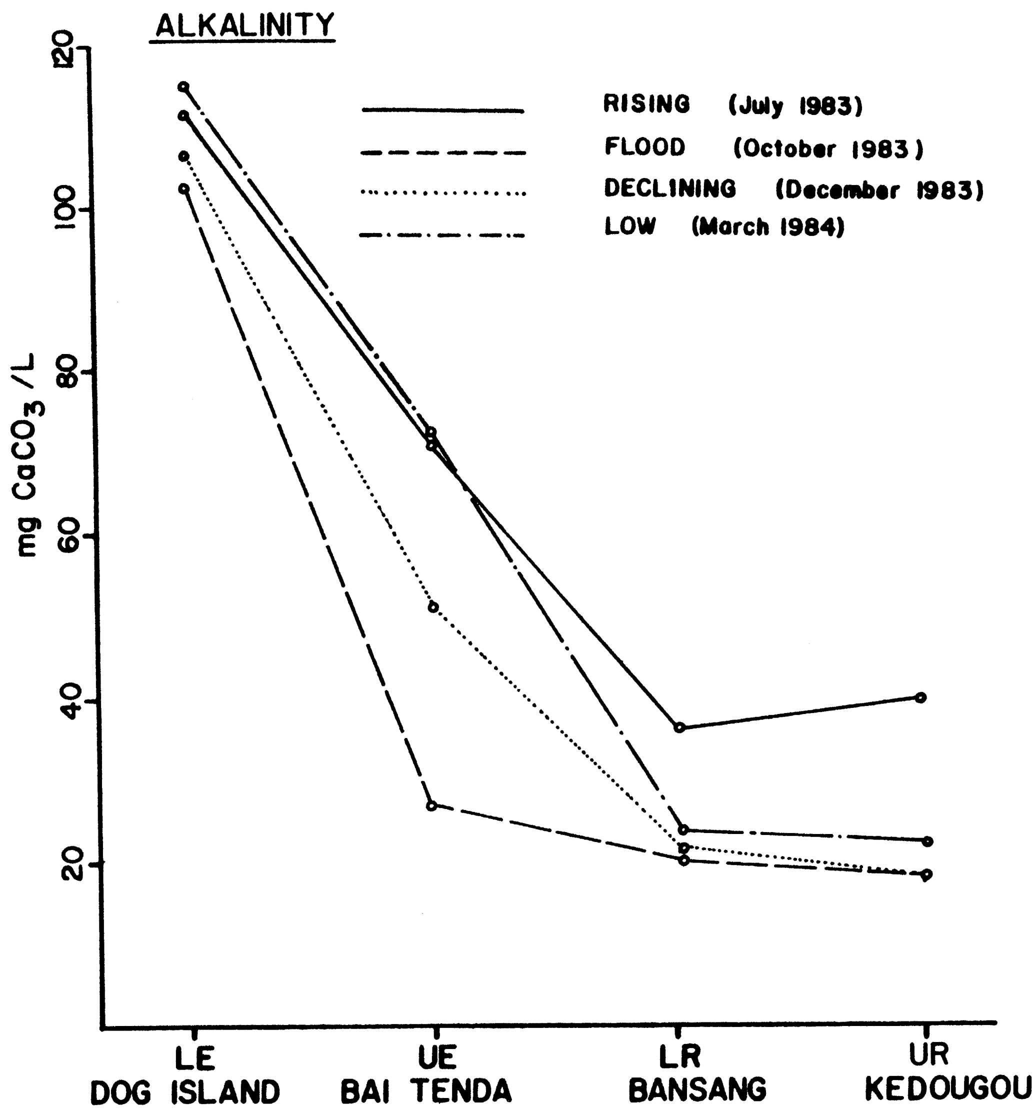

FIGURE 22. Mean alkalinity concentrations and standard errors for each zone and season.

tent in July just prior to dilution by runoff. The major source of bicarbonate loading was from runoff. Even though the runoff was more dilute in bicarbonate than river water, due to the volume of runoff, the loading was greater. The loading of bicarbonate was estimated at 18,455 metric tons/yr at Kedougou and 30,107 metric tons/yr at Bansang. The Bansang estimate is 2.8 times less than the Lesack et al. (1984) estimate of 85,200 metric tons in 1980-81. This can for the most part be explained by the approximately 2.5 times higher discharge in 1980-81 compared to 1983-84. The loss rates of bicarbonate for the catchments above Kedougou and Bansang were 2,460 $kg/km^2/yr$ and 719 $kg/km^2/yr$. The 1983-84 calculations indicated that over seven times more bicarbonate came from the headwaters region above Kedougou than from the continental subbasin region between Kedougou and Bansang.

The lower reaches of the Gambia River for the purpose of discussion can be roughly partitioned into regions based on alkalinity concentrations (Fig. 23). This can be done by considering the relative levels, seasonal variability, and longitudinal location. Extending from the river mouth to approximately 30 km upstream existed a reach of the river that displayed very high alkalinity (usually >100 mg $CaCO_3$/L) and moderate seasonal variability. This region was predominantly salt water and considered part of the lower estuary zone including the sampling site. The upper estuary zone was a region of steadily declining alkalinity gradients which paralleled the salinity gradient. This region displayed high seasonal variability in alkalinity concentrations following the salinity changes with streamflows. Alkalinity was highly correlated with salinity using samples collected both at the upper estuary sampling site and between the main sampling areas (Fig. 23). Extending upriver approximately 225 km from the river mouth and covering the freshwater

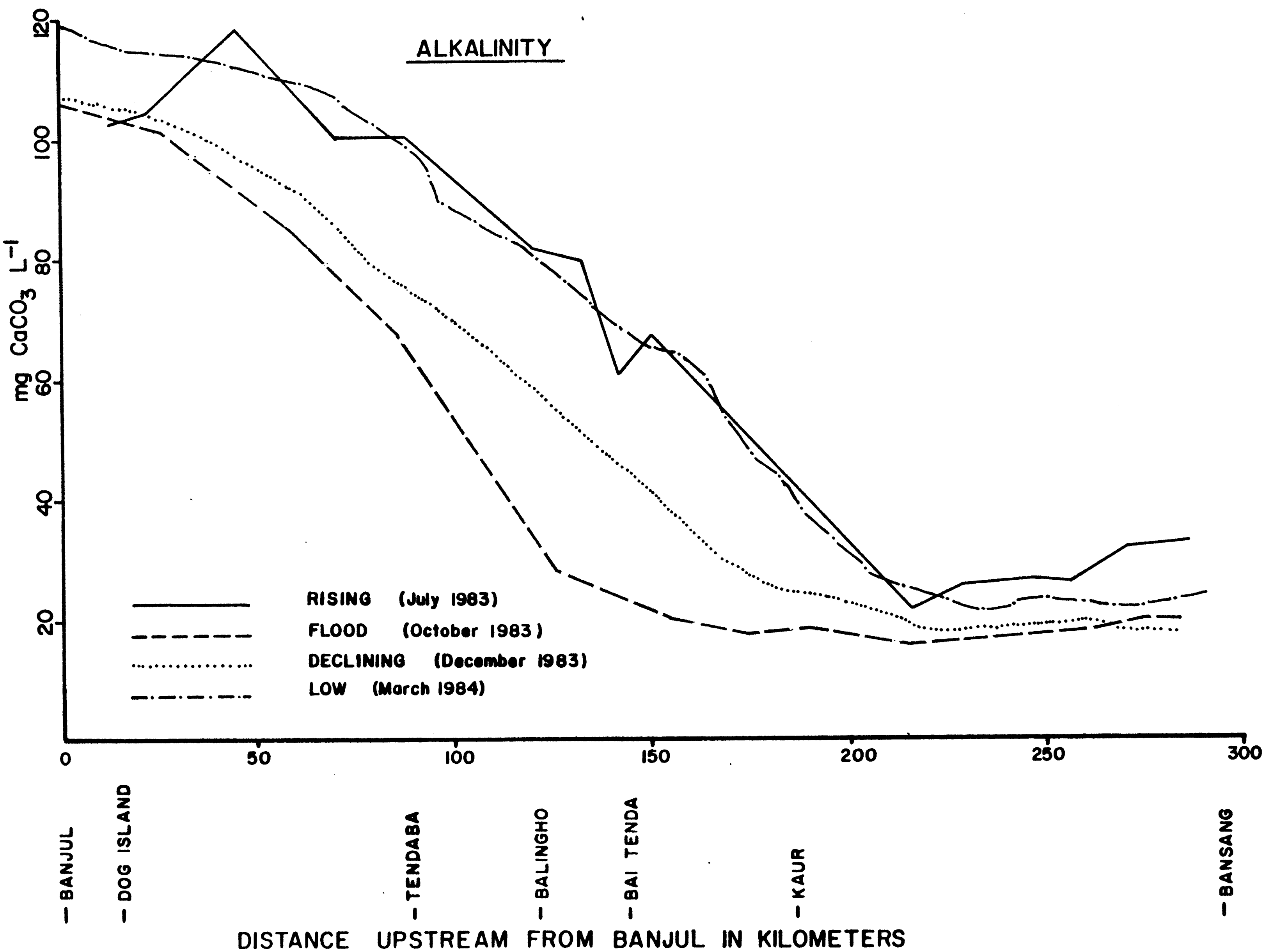

FIGURE 23. Distribution of alkalinity by season in the lower 300 km of the Gambia River.

portion of the river, the alkalinities were low to very low depending on the season.

The seasonal cycle of alkalinity in the river inversely followed river discharge. During the first field trip all locations displayed high values because the dilution from runoff had not yet occurred. In October, following the annual rains, the lowest values at all locations were observed. Lesack et al. (1984) found that bicarbonate in the Gambia River decreased hyperbolically with discharge. The lower values reported by the 1980-81 study compared to this study directly reflect the higher discharge in 1980-81. In December the freshwater locations had undergone only a very small increase in alkalinity concentrations since the October field trip; at the upper river location the October and December concentrations were not statistically different. In contrast, the upper estuary location had almost doubled its alkalinity as a result of the reintroduction of salt water in this region. The lower estuary also increased between October and December, but to a lesser degree than the upper estuary because of the smaller salinity changes that took place in this zone. By March the effect of the annual rains was minimal, and increases in alkalinity at all the locations were observed. The freshwater regions displayed increases evidently due to groundwater input with some evaporation effect (evaporation rates at Kedougou ranged from 4.8 to 7.5 mm/day or up to 6.75 mm/90 days). The estuarine zones displayed increases due to evaporation and salinity increases. Again, the upper estuary zone underwent the greatest annual change because of saltwater intrusion.

pH

The waters of the Gambia River were generally slightly alkaline. Over the course of the Gambia River Basin Study, pH ranged from 6.30 to 8.80 (Table

15). The estimated yearly average for the river was 7.47. The lower estuary consistently had higher pH values than the other zones, resulting from the high concentrations of salt water in this region. There was a significant positive correlation between pH and salinity, hence pH values in the estuary generally declined with distance upriver. In the upper estuary zone, respiration of high concentrations of suspended solids during flood stages probably accounted for depressed pH values. The lowest pH values observed during a field trip were usually found at the upper river site. Generally pH declined with discharge, resulting in relatively low values during the October field trip.

The yearly estimated average pH values for the study sites along the river were 7.93, 7.22, 7.40, and 7.23 for the lower estuary, upper estuary, lower river, and upper river, respectively. These values indicate moderate longitudinal variability due primarily to saltwater intrusion. Seasonal variability was lowest in the lower estuary due to the high buffering capacity of salt water (Fig. 24). Seasonal variability increased with distance from the river mouth. Sampling variability was low for the estuary, higher for the freshwater zones, and usually highest at the upper river site. Longitudinal values and seasonal variability were very often greater than variability within any one zone during one field trip. The major factor contributing to variability at one zone during one field trip was time of day/tide.

The Gambia River was partitioned into distinct regions based on pH values (Fig. 25). This can be done by considering relative levels, seasonal variability, and longitudinal values of pH. Because this parameter is influenced by river discharge, the boundaries of these regions will vary within and among years. Extending from the river mouth to about 100 km upstream existed

TABLE 15. pH results from the Gambia River, 1983 and 1984.

	Rising	Flood	Declining	Low	
			Minimum		
Lower Estuary	7.87	7.74	7.91	7.81	7.74
Upper Estuary	7.29	6.96	7.02	7.21	6.96
Lower River	6.30	6.69	7.47	7.58	6.30
Upper River	6.40	6.50	6.81	6.72	6.40
	6.30	6.50	6.81	6.72	6.30
			Maximum		
	Rising	Flood	Declining	Low	
Lower Estuary	7.99	7.94	8.08	8.02	8.08
Upper Estuary	7.58	7.16	7.13	7.49	7.58
Lower River	7.50	7.52	7.64	7.78	7.78
Upper River	8.00	7.55	7.76	7.51	8.00
	8.00	7.94	8.08	8.02	8.80
			Mean		
	Rising	Flood	Declining	Low	
Lower Estuary	7.94	7.86	7.98	7.95	7.93
Upper Estuary	7.41	7.03	7.08	7.39	7.22
Lower River	7.03	7.30	7.55	7.67	7.40
Upper River	7.41	7.04	7.34	7.09	7.23
	7.36	7.36	7.51	7.63	7.47
			Standard Deviation		
	Rising	Flood	Declining	Low	
Lower Estuary	.03	.05	.03	.05	.06
Upper Estuary	.05	.06	.03	.06	.18
Lower River	.36	.28	.03	.04	.33
Upper River	.53	.26	.25	.23	.37
	.42	.39	.36	.27	.38
			Coefficient of Variation		
	Rising	Flood	Declining	Low	
Lower Estuary	.40	.60	.40	.60	.80
Upper Estuary	.70	.90	.40	.80	2.50
Lower River	5.10	3.80	.40	.50	4.40
Upper River	7.10	3.70	3.40	3.30	5.10
	5.60	5.30	4.80	3.60	5.00

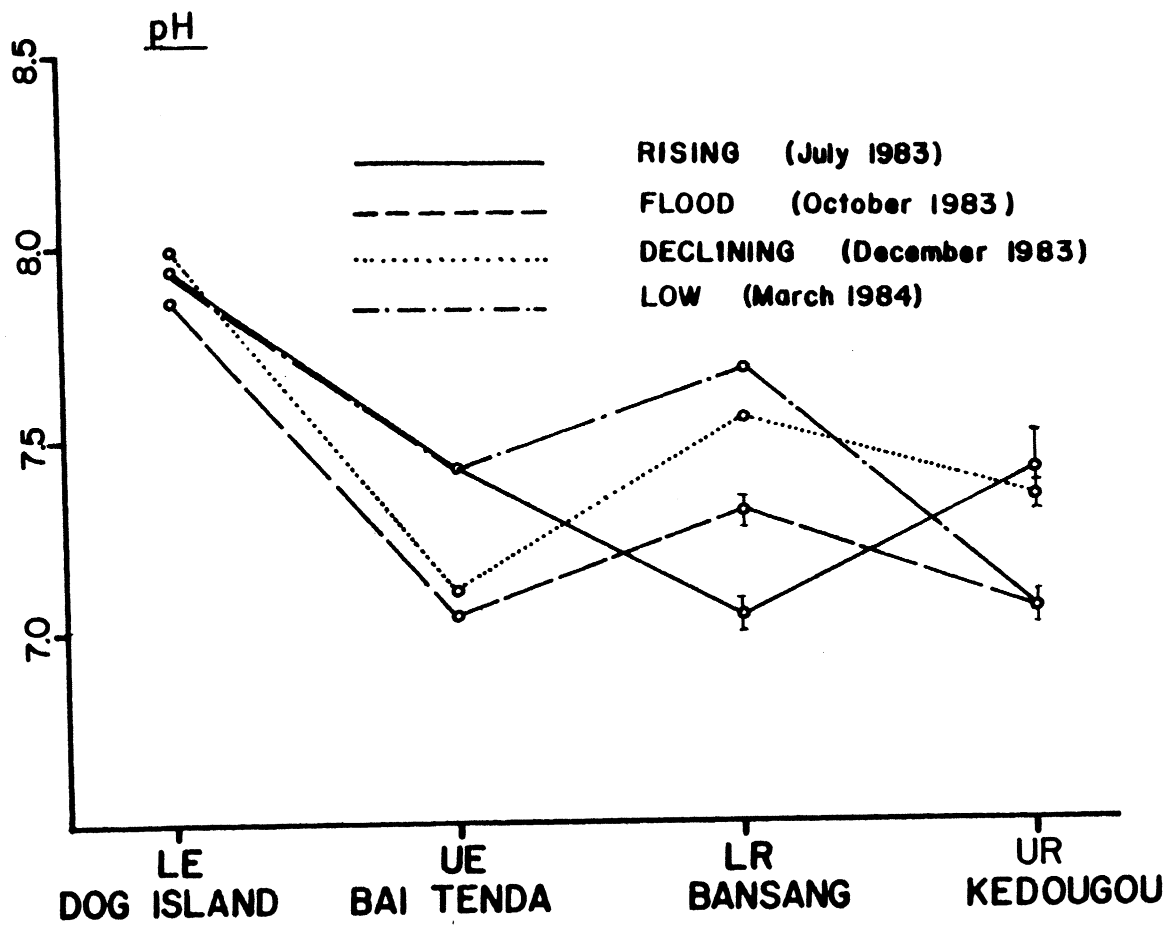

FIGURE 24. Mean pH levels and standard errors for each zone and season.

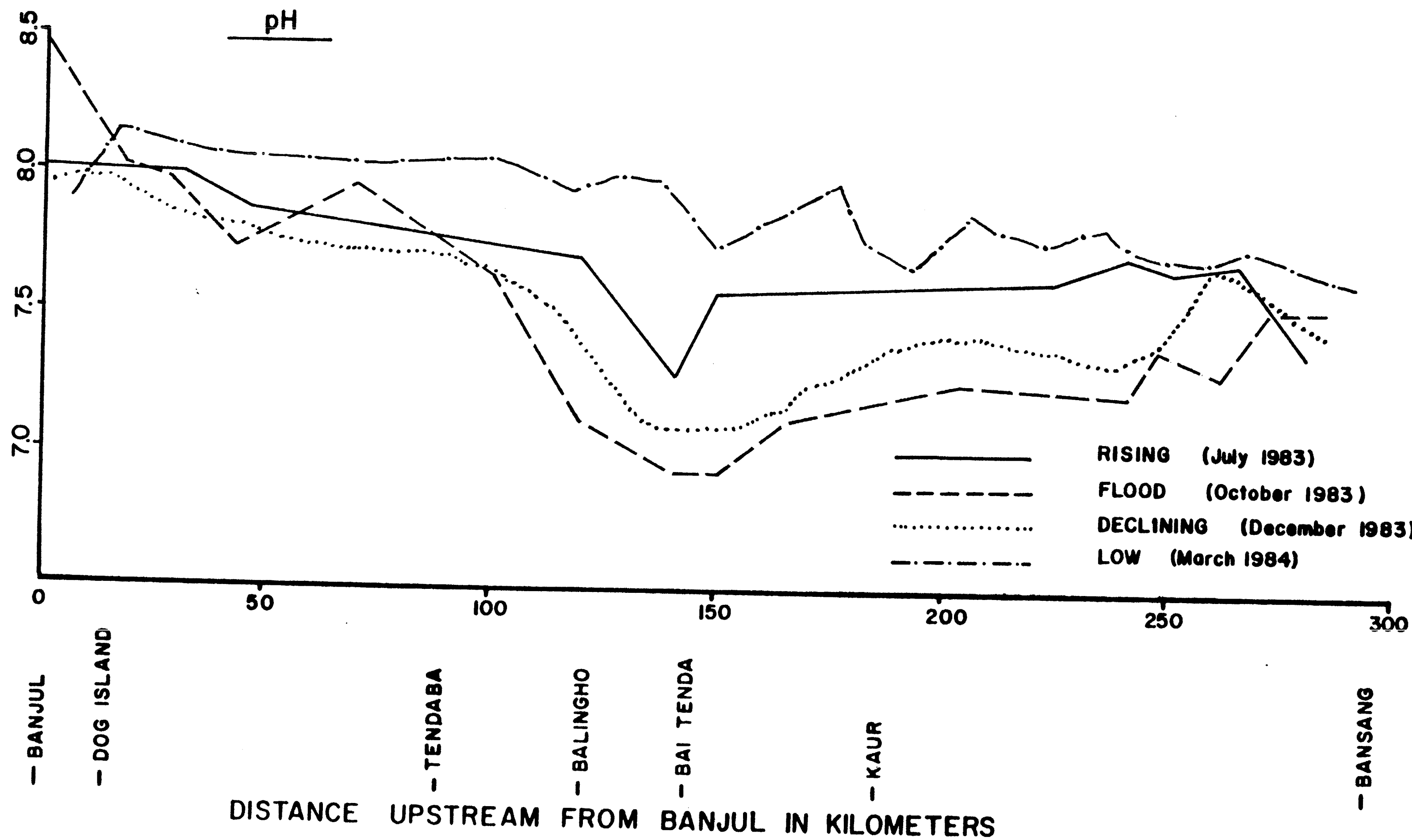

FIGURE 25. Distribution of pH by season in the lower 300 km of the Gambia River.

a section of which displayed generally higher pH values that the rest of the river. Usually these high pH values slowly decreased with distance upriver, yielding a positive correlation between pH and salinity. This correlation was highest during the flood stages. The lower estuary zone was located in this area. This zone had an average pH of 7.93 over the course of the study with mean values ranging from 7.86 to 7.95. The seasonal and sampling variability at this location was very low due to the high buffering capacity of saltwater.

Extending for around 50 km on either side of the upper estuary sampling site was a region that during flood stages showed a well defined depression in pH values relative to those reaches of the river that border it (Fig. 25). The minimum pH values in this region were found near Bai Tenda which had an average pH value over the course of the study of 7.22. The range of values over the year was about twice as large for the samples collected between the lower and upper estuary sampling locations than for those taken at the upper estuary site. Seasonal variability at the study site was moderate and much higher than sampling variability. The annual range of pH at the upper estuary sampling site was also very large, with values between 6.96 to 7.58. Respiration of the high concentration of suspended solids found during the high water stages probably produced the low pH values.

Extending from near Kaur to Bansang was a section of the river with pH values that were usually intermediate relative to the estuary sites. The lower river sites had an average pH value over the course of the study of 7.40. Seasonal and within field trip variability during the first two field trips was high. These variances could have resulted from the low buffering capacity of the water and the effect of runoff during the first two field trips.

Kedougou had an annual average pH value of 7.23 which was similar to the other sites up river from the lower estuary. During each field trip, with the exclusion of the lower estuary site, the highest pH values were usually observed here. Also, the lowest pH values of any sites were found here. These extreme values were reflected in the very large annual range of pH which extended from 6.40 to 8.00.

The seasonal cycle of pH in the river inversely followed discharge. All the sites except the upper river displayed a decline in pH following the annual rains (Fig. 24). The upper river site was already experiencing the effects of runoff during the July field trip. During the December sampling with passage of the annual flood, pH had increased at all the sites.

CHLOROPHYLL AND PHAEOPIGMENT

Chlorophyll was measured in the Gambia River as an approximate indication of algal biomass. In this context, chlorophyll was viewed as a biological variable tied to plankton ecology and is discussed in more detail in Healey et al. (1985). But, because chlorophyll measurements were made on a high frequency basis, the same amount of chlorophyll data was available as for the other chemical variables discussed above. As a result, chlorophyll was viewed both as a chemical characteristic of Gambia River water and as an estimate of plankton biomass.

The overall mean concentration of chlorophyll in the Gambia River was 2.99 μg/L, which is a moderate concentration on a world-wide basis (Wetzel 1983). The range of chlorophyll concentrations among the different zones was considerable as was the range within one zone. Without exception, the upper river zone had the lowest mean chlorophyll concentrations throughout the course of the study. The highest mean concentration in the upper river zone

was 1.12 μg/L during the declining waters field trip, while the other field trips had means well below 1.00 μg/L (Table 16). Concentrations in the other zones were higher, although a strong seasonal factor was evident. Concentrations in the lower river were usually the highest in the river except during the low water field trip, when the upper estuary zone had the highest concentrations (Table 16). Lower estuary chlorophyll values were somewhat more uniform among all seasons than the other zones, although a distinct annual cycle was present (Fig. 26). Mean chlorophyll concentrations outside of the upper river zone usually ranged between 2 and 4 μg/L with two exceptions; a very high (12.7 μg/L) mean was observed in the lower river during the rising water field trip, as was a very low mean (0.59 μg/L) in the upper estuary during the flood water field trip.

The maximum chlorophyll a value (20.83 μg/L) observed in the Gambia River was measured in the lower river zone during rising water and the lowest value (.09 μg/L) was found in the upper river zone at flood water yielding an annual range of 20.74 μg/L (Table 16). In the two estuarine zones the range increased with higher salinities, while in the freshwater zones the range decreased in samples collected farther upstream. The samples taken during the rising water period in the lower river constituted a marked exception. The range of these samples was 15.46 μg/L, twice that of any other zone, and the mean value for this group was 12.69 μg/L, three times higher than the mean for any other zone.

Because chlorophyll is biological in origin, it cannot be attributed directly to some physical process such a change in runoff, etc. Rather, a series of physical processes generally stimulates plankton growth which is reflected in elevated chlorophyll concentrations (Steeman-Nielson 1975). The

TABLE 16. Chlorophyll a results (μg/L) from the Gambia River, 1983 and 1984.

Minimum

	Rising	Flood	Declining	Low	
Lower Estuary	1.44	.64	.73	.74	.64
Upper Estuary	1.66	.31	.60	1.95	.31
Lower River	5.37	1.53	1.02	1.15	1.02
Upper River	0.00	.09	.82	.34	.09
	1.44	.09	.60	.34	.09

Maximum

	Rising	Flood	Declining	Low	
Lower Estuary	5.25	5.20	5.81	8.15	8.15
Upper Estuary	6.25	1.42	3.07	8.09	8.09
Lower River	20.83	3.49	4.14	3.30	20.83
Upper River	0.00	.72	1.34	1.46	1.46
	20.83	5.20	5.81	8.15	20.83

Mean

	Rising	Flood	Declining	Low	
Lower Estuary	3.89	1.96	1.94	3.11	2.53
Upper Estuary	3.71	.59	1.13	4.01	2.37
Lower River	12.69	2.34	2.41	2.01	4.61
Upper River	0.00	.33	1.12	.81	.75
	7.36	1.50	1.74	2.87	2.99

Standard Deviation

	Rising	Flood	Declining	Low	
Lower Estuary	.90	.89	1.02	1.54	1.36
Upper Estuary	.84	.17	.35	1.19	1.69
Lower River	3.77	.40	.60	.30	4.75
Upper River	0.00	.14	.14	.30	.40
	5.04	.98	.86	1.47	3.17

Coefficient of Variation

	Rising	Flood	Declining	Low	
Lower Estuary	23.10	45.20	52.80	49.60	53.80
Upper Estuary	22.50	29.10	30.50	29.80	71.60
Lower River	29.70	17.30	24.90	15.20	102.90
Upper River	0.00	43.50	12.00	36.90	53.00
	68.40	65.70	49.30	51.30	106.20

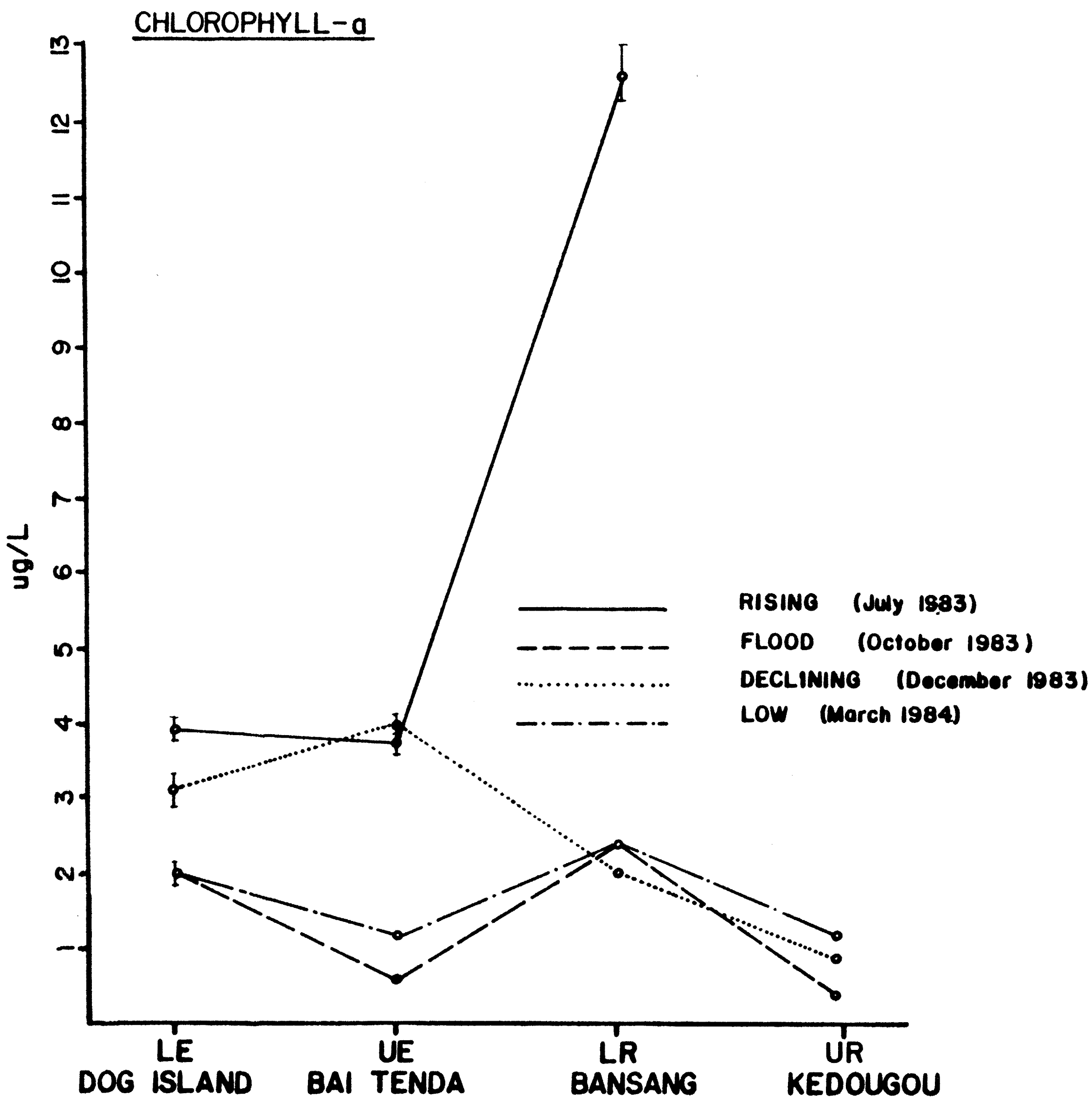

FIGURE 26. Mean chlorophyll a concentrations and standard errors for each zone and season.

net conclusion was that algae in the Gambia River were primarily light-limited because of turbid river waters (Healey et al. 1985). Under certain conditions the water in the river cleared and algae growth was promoted. Such conditions appeared to prevail during the early phases of the annual flood, when inputs of nutrients from runoff were high, but the water was not highly turbid; these conditions were apparently present in the lower river zone during the July (rising water) field trip, yielding a very high mean chlorophyll concentration. In contrast, during the peak of the annual flood, river waters were especially opaque and algae biomass was very low. Flood waters field trip chlorophyll concentrations were generally the lowest of the year (Table 16). In a few cases, nutrient concentrations may have limited algal growth and held chlorophyll concentrations to low levels as opposed to light. Such conditions were evident in the upper river zone where small pools were relatively clear, but had extremely low soluble nitrogen concentrations. The lower estuary zone behaved somewhat independently of the rest of the river because this zone derived its characteristics from the intrusion of sea water, which was slightly more productive than the freshwater river.

Samples collected between the primary sampling locations revealed several distinct regions of contrasting chlorophyll concentrations. During the rising waters field trip (July), two distinct regions of elevated chlorophyll concentrations were observed in the river. The first region was between 30 and 90 km upstream with concentrations reaching almost 10 μg/L (Fig. 27). Almost 200 km further upstream, a region of very high chlorophyll concentrations was observed with levels in excess of 15 μg/L. The contrast between this upstream region and the waters of the upper estuary slightly downstream was striking, with concentrations over four times as high in one location com-

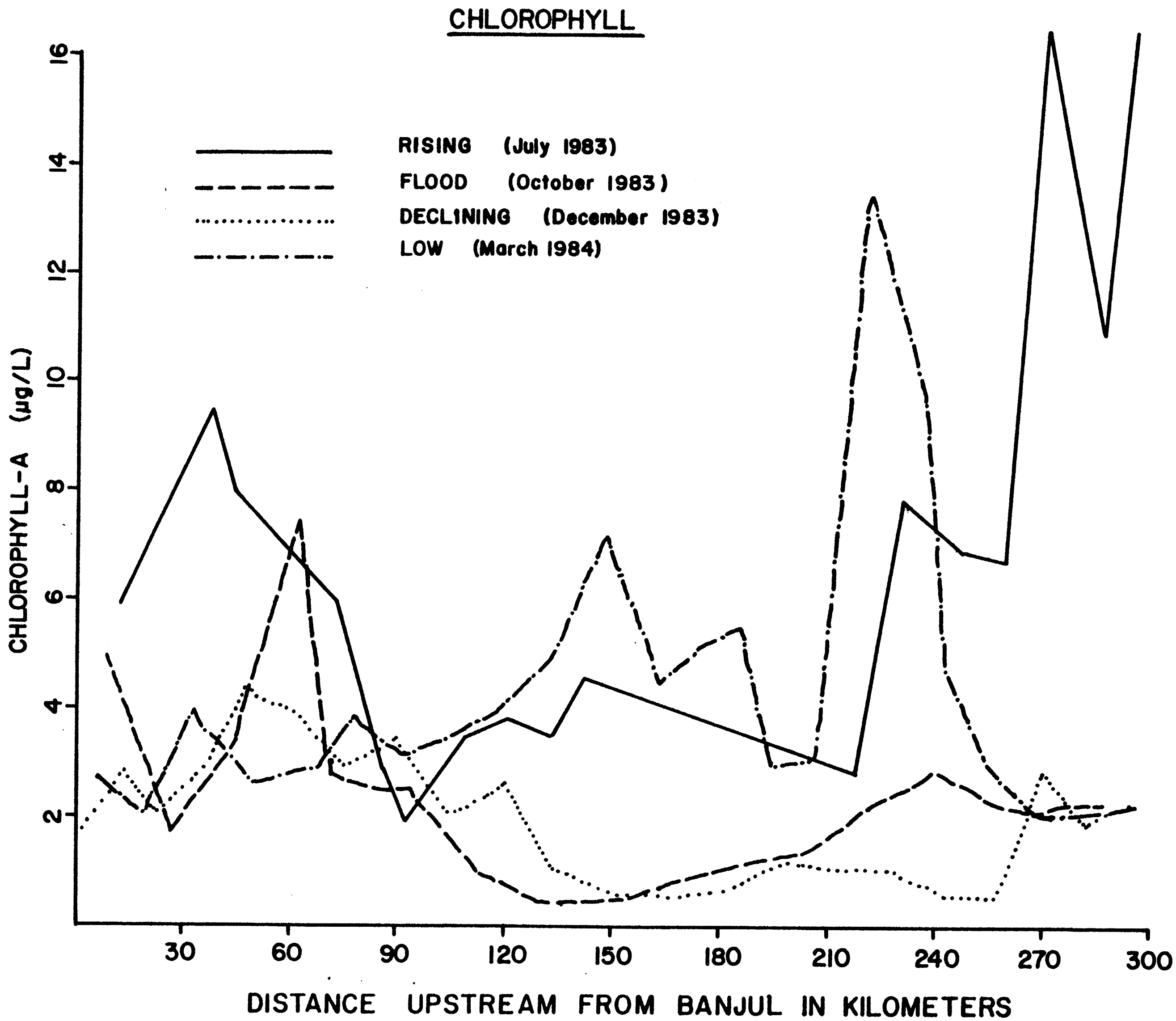

FIGURE 27. Distribution of chlorophyll a by season in the lower 300 km of the Gambia River.

pared to the other. During the following field trip in October (flood waters), one of the two regions of high chlorophyll persisted, although concentrations at this location were slightly lower than July. The region was found beginning approximately 50 km upstream and extending to 80 km upstream (Fig. 27). There were no regions of elevated chlorophyll concentrations during the declining waters field trip (December), when concentrations generally reached the annual nadir throughout the river. During March (low water field trip), the two regions of high chlorophyll concentrations observed earlier had become reestablished in approximately the same locations (Fig. 27). Chlorophyll levels were somewhat lower in March compared to July, but still reached well over 10 μg/L at 240 km upstream. Evidently some feature of the Gambia River allowed the development of these high-chlorophyll regions during the seasons of low streamflows. But the annual flood appeared to disrupt these two regions.

Phaeopigments are the degradation products of chlorophyll and usually indicate the presence of recently decayed plant material. Comparison of chlorophyll to phaeopigment concentrations indicates if the algal crop is composed of a large amount of dead cells. In an environment such as the Gambia River, a large amount of dead plant material is the normal situation. The waters of tropical rivers carry a large amount of plant debris which enters the river from vegetation lining the banks.

The Gambia River proved no exception to the hypothesis that tropical rivers carry a large amount of detritus. Mean phaeopigment concentrations were 1.27 μg/L, or over 40% of chlorophyll concentrations (Table 17). This compares with approximately 10% for actively growing plankton populations (Fogg 1975). In general, phaeopigment concentrations in the Gambia River fol-

TABLE 17. Phaeopigment results (µg/L) from the Gambia River, 1983 and 1984.

Minimum

	Rising	Flood	Declining	Low	
Lower Estuary	.38	.14	.16	.35	.14
Upper Estuary	.80	1.12	.53	.27	.27
Lower River	0.00	.61	.53	.12	0.00
Upper River	0.00	.39	.34	.05	.05
	0.00	.14	.16	.05	0.00

Maximum

	Rising	Flood	Declining	Low	
Lower Estuary	4.13	2.27	2.16	6.44	6.44
Upper Estuary	3.44	4.64	5.70	8.57	8.57
Lower River	5.31	1.53	1.68	.84	5.31
Upper River	0.00	1.10	.60	.26	1.10
	5.31	4.64	5.70	8.57	8.57

Mean

	Rising	Flood	Declining	Low	
Lower Estuary	1.44	.79	.68	2.13	1.23
Upper Estuary	1.77	2.31	1.88	1.32	1.81
Lower River	1.52	1.14	.86	.50	.99
Upper River	0.00	.68	.49	.17	.49
	1.61	1.30	1.07	1.23	1.27

Standard Deviation

	Rising	Flood	Declining	Low	
Lower Estuary	.85	.37	.42	1.26	1.02
Upper Estuary	.62	.55	1.16	1.22	1.01
Lower River	1.02	.20	.19	.15	.63
Upper River	0.00	.21	.07	.05	.24
	.85	.75	.87	1.20	.95

Coefficient of Variation

	Rising	Flood	Declining	Low	
Lower Estuary	58.90	47.20	62.00	59.50	82.90
Upper Estuary	34.90	23.60	61.70	92.00	55.70
Lower River	67.30	17.30	22.00	30.00	63.90
Upper River	0.00	31.30	14.70	30.50	49.40
	52.80	57.40	81.30	98.20	75.10

lowed chlorophyll concentrations, indicating that the river carried a large load of decaying plant material. The exception to this pattern was in the lower river zone during the rising water field trip. The large mean chlorophyll values were not accompanied by high phaeopigment values. These results suggest that the algal population associated with the high chlorophyll concentrations was composed of actively growing cells; this was confirmed by primary productivity measurements (Healey et al. 1985). In contrast, river waters with high suspended solids loads were characterized by extremely high phaeopigment (and hence detritus) levels.

With the exception of the low water field trip, phaeopigment concentrations were highest in the upper estuary, followed by lower estuary, lower river, and upper river zones in that order (Table 17). The high phaeopigment concentrations found in the upper estuary may have been caused by the tidal flushing of detritus out of the mangrove swamps. For the low water sampling period, phaeopigments were at a maximum in the lower estuary and decreased in each succeeding zone moving upstream (Table 17).

The phaeo-fraction was generally higher for the flood and declining water stages, indicating the entrainment of dead plant material during flood water conditions. This was especially apparent in the upper estuary and upper river zones. Phaeopigment plotted as a function of distance upstream showed two areas of high concentration during the rising water period. One area was located between 40 km and 70 km upstream and the other between 260 km and 300 km (Fig. 28). For the flood water, declining water, and low water periods a single area of peak phaeopigment concentration was identified for each season at 125 km, 80 km, and 200 km, respectively.

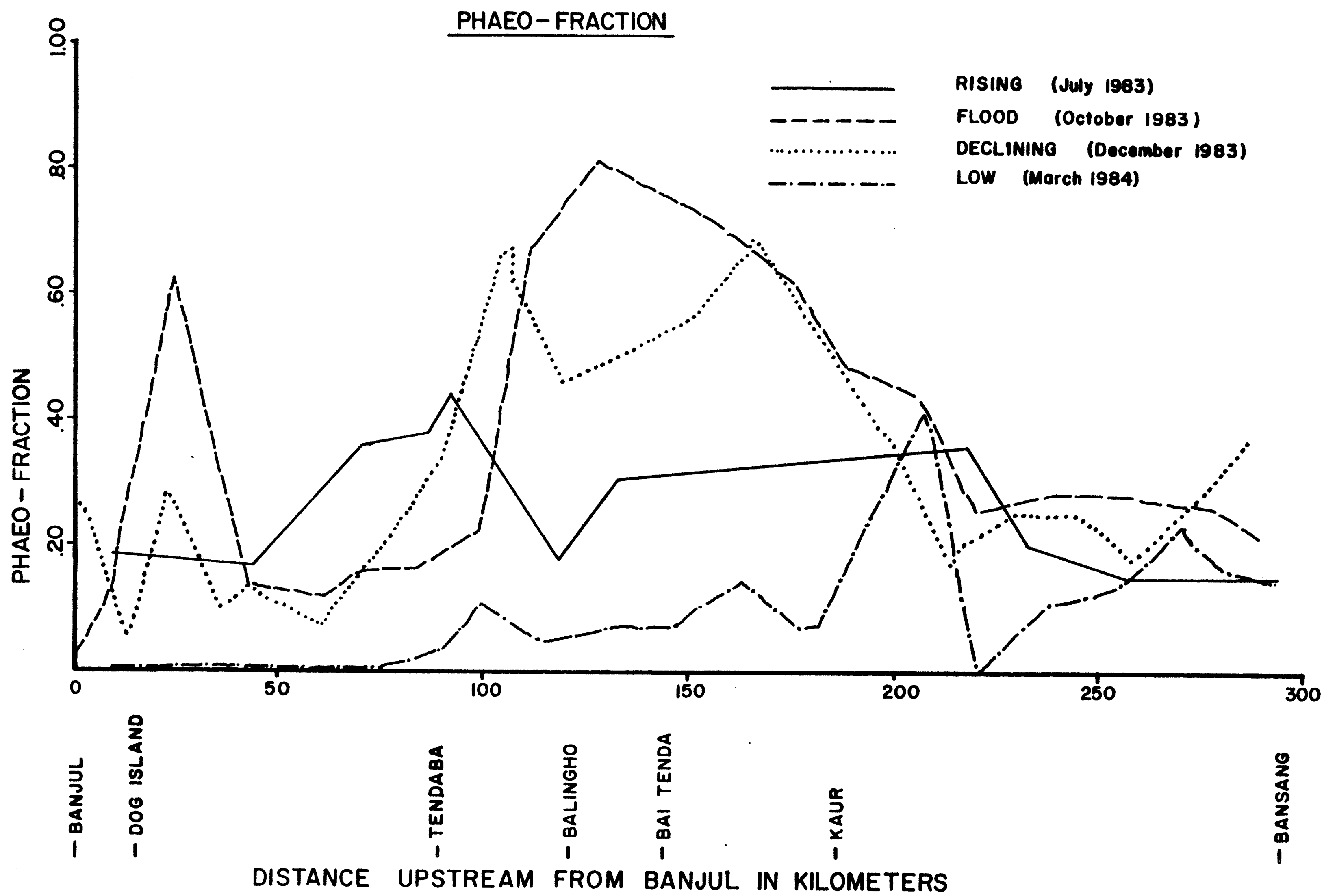

FIGURE 28. Distribution of phaeopigments by season in the lower 300 km of the Gambia River.

ECOLOGICAL ZONES OF THE GAMBIA RIVER

LOWER ESTUARY

Physical Characteristics

The lower portion of the Gambia River was defined as the lower estuary zone, and extended from the river mouth to Mootah Point. The most important characteristic of this zone was that it was primarily an extension of the coastal marine waters into the wide, slow-flowing river. In effect, the lower estuary zone was a tongue of the sea extending inland about 25 km.

The physical characteristics of the lower estuary were very conducive to allowing the penetration of salt water into the river throughout most of the lower reaches, where the Gambia River was relatively shallow and fairly wide. In many places the lower estuary was over 5 km wide, and over 15 km wide in a few locations. Bathymetric profiles and navigational charts showed a broad, shallow river averaging about 2 m deep with a well-defined channel up to 10 m deep. The channel did not run down the middle of the river, but rather tended to run along the "inside" of most of the bends in the river. On the "outside" of the bends, sediment accumulated and extensive shallow mud banks extended up to 2 km from the shore.

The primary sampling site in the lower estuary was a large east-west stretch of the river between Dog Island Point and Lamin Point. The river was slightly over 6 km wide at this point which was 12-18 km upstream from the river mouth at Banjul. Bathymetric transects taken across the river at four locations indicated a small (200-300 m) mud and rock shelf extending out from the north bank. A large mud flat extended about 2 km out from the south bank. This south bank mud flat was often only 0.5 m below the water surface at low

tide. The central 3.5 km of the river included a large trough-shaped channel that had a maximum depth of 10 m. The bottom composition of the river was almost entirely soft, silty mud.

Throughout the entire length of the lower estuary zone of the Gambia River extensive Rhizophora and Avicennia mangrove forests lined the banks. The banks of the river are cut by numerous small tidal creeks (bolons). These bolons meander well beyond the river banks, allowing penetration of river water several km inland from the actual bank of the river. During high tide extensive portions of the land on both sides of each bolon are covered with 0.25 to 0.5 m of water. These conditions are ideal for the extensive growth of mangrove forests.

The water in the lower portion of the Gambia River was well mixed from tidal and wind-generated forces. The wide, shallow river, which had generally uniform temperatures and salinities from surface to bottom, was evidently well mixed by wind waves. Waves of up to 1 m in height were commonly observed at the primary sampling site. The east-west orientation of much of the river channel allowed prevailing sea breezes or land breezes to blow along the length of the river. Perhaps even more important than the wind mixing was tidal mixing in the lower estuary. The wide mouth of the Gambia River allowed tidal waves to move readily up into the river. Tidal amplitude and period in the lower estuary were very similar to those in Banjul; the tidal wave arrived at Dog Island Point approximately 40 minutes after passing Banjul. As will be shown below, tidal mixing was a major process which controlled the distribution and concentration of many suspended and dissolved materials. Tidal fluctuation also had an important effect on the behavior and distribution of many organisms (Dorr et al. 1985; van Maren 1985; Healey et al. 1985).

Aquatic Characteristics

The aquatic environment was characterized by high-salinity salt water. During the first half of the 20th century, the annual flood had sufficient freshwater discharge to carry fresh waters all the way to Banjul on ebbing tides (HHL 1984). Since 1950, diminishing levels of rainfall have reduced runoff to the point where in 1983 fresh water was observed no farther downstream than Tendaba, about 90 km up-river from Banjul; the lower estuary zone remained brackish year-round. At the lower estuary sampling site, salinities were never observed below 28.5 parts per thousand (ppt) (Fig. 29). Mean salinities never fell below 32.3 ppt. Those salinities below 31 ppt were primarily observed near the banks of the river and were attributed to local runoff during or just after the rainy season. The consistently high salinities of the lower estuary since 1950 have produced an environment favorable for the invasion of many forms of marine flora and fauna.

The penetration of high-salinity seawater into the lower portion of the Gambia River produced a very consistent aquatic environment. Seawater is a well buffered medium with extremely consistent ionic ratios, alkalinities, and pH (Strickland and Parsons 1972). The alkalinities and pH values observed in the lower estuary reflected the consistency of the salt water (Fig. 29). Over the course of the four field trips, mean alkalinity values ranged from 103 to 115 mg $CaCO_3$/L (Table 14). The range about the mean from each field trip was small, never exceeding 10 mg/L.

The annual fluctuations in pH were extremely small, with the means from each of the four field trips varying by no more than 0.09 standard units (Table 15). Figure 29 shows that the range in pH during any one field trip actually exceeds the annual range of the means; typically the range in pH dur-

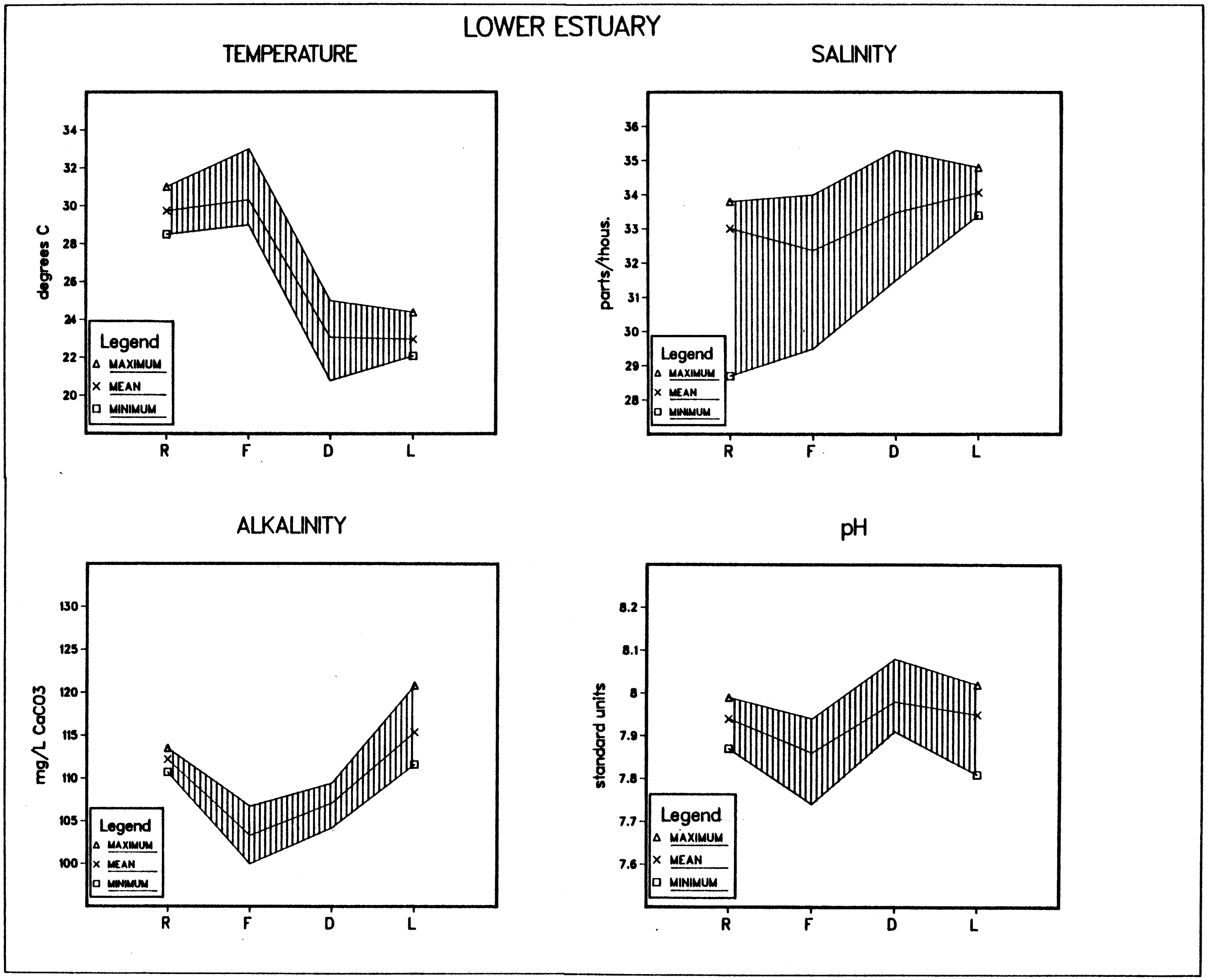

FIGURE 29. Means and ranges of physical and chemical variables for the lower estuary zone.

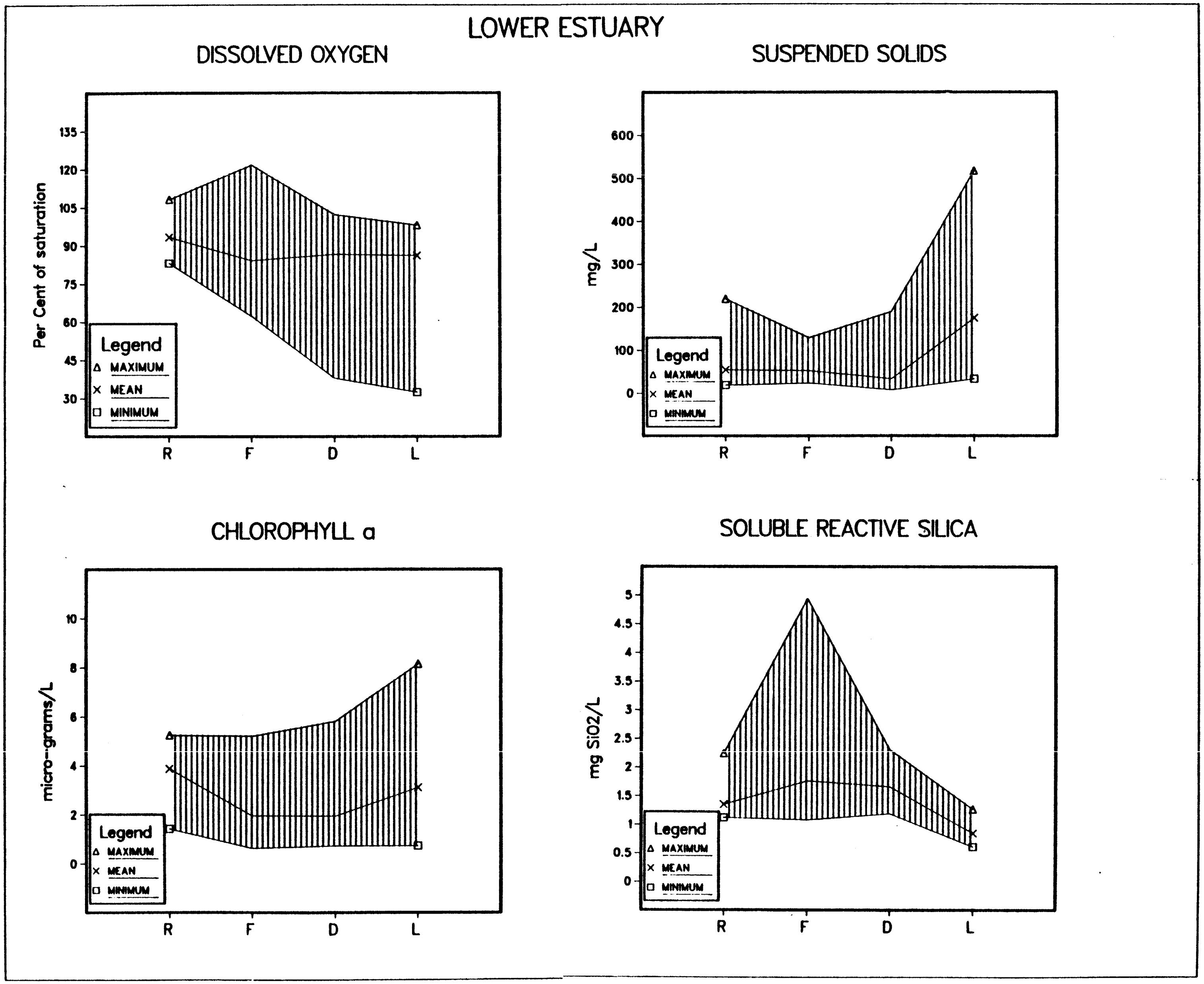

FIGURE 29. (continued).

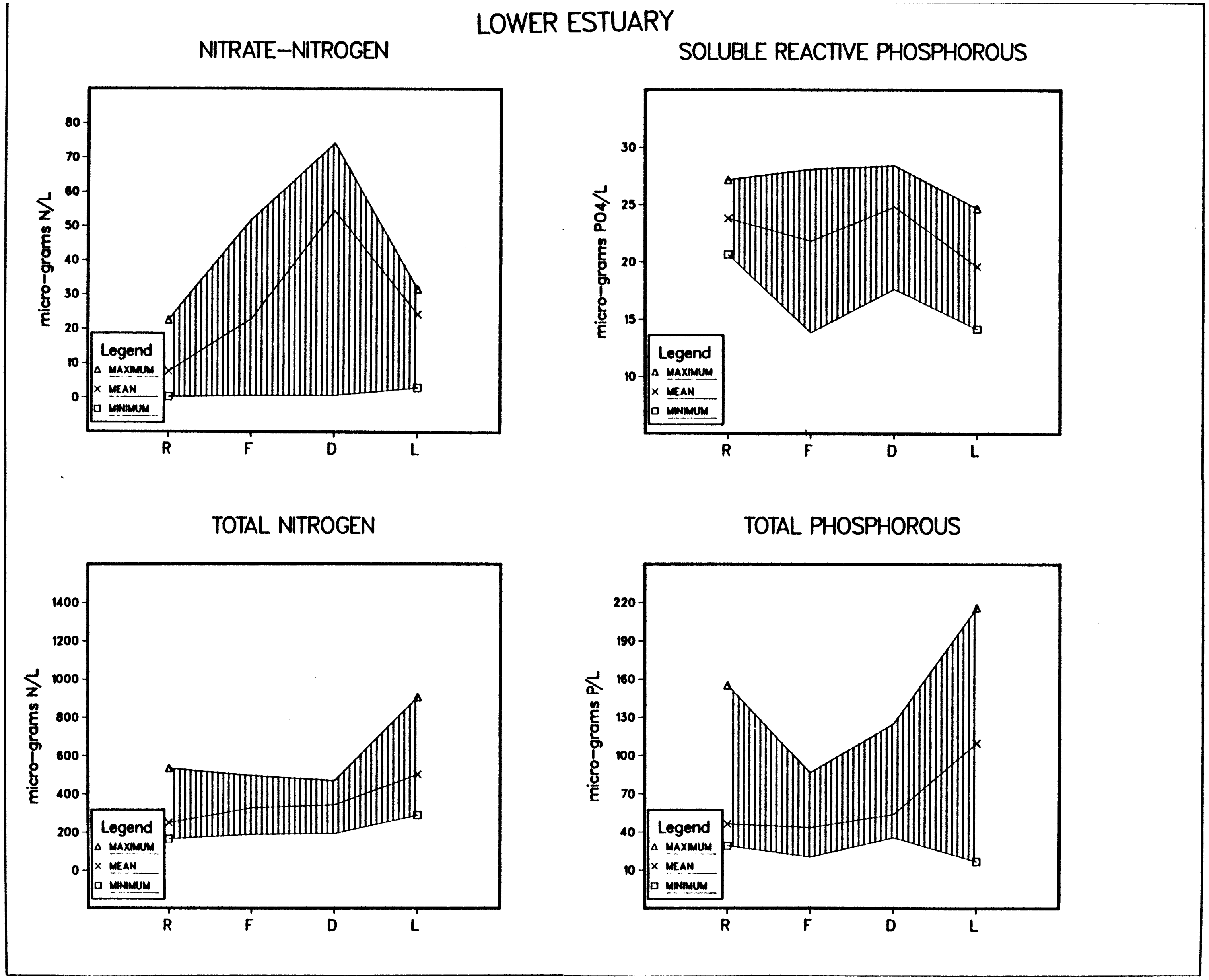

FIGURE 29. (continued).

ing any one field trip was about 0.18 standard units. The annual ionic consistency of the water in the lower estuarine portion of the river has important implications for the flora and fauna. The lack of extreme conditions and high degree of similarity to the coastal marine environment encourages the colonization of truly marine organisms at the expense of estuarine organisms (McLusky 1971). Only those organisms living at the edges of the river were likely to encounter any fluctuations in their aquatic environment, and that was primarily slightly lower (4 ppt) salinities for 3 to 4 months per year.

The waters of the lower estuary were also relatively consistent in that they were highly oxygenated throughout the year (Fig. 29). Winds and tides evidently mixed lower estuary waters to the extent that dissolved oxygen levels fell below 60% saturation on only two occasions; these were samples collected near the bottom of the deepest portion of the river. Mean percent oxygen saturation values were fairly consistent over the four field trips, ranging from 84% to 93% (Table 13). These results demonstrated that organisms living in the lower estuary zone should never encounter low oxygen concentrations which could effect their abundance and distribution.

The one aspect of the aquatic environment which did undergo a large amount of annual change was the thermal cycle. The coastal waters of West Africa are greatly influenced by the movement of the North Equatorial Current (Sverdrup et al. 1942). This current migrates southward during the European winter (November or December), and creates a southward coastal current through April or May. The water transported by this current is considerably cooler than the surface runoff in West Africa or the offshore oceanic waters (Sverdrup et al. 1942). As a result, there was a dramatic drop in coastal water temperature between the flood (October) and declining waters (December)

field trips. The temperatures of the lower estuary responded exactly the same as the coastal waters and dropped from a mean of slightly over 30°C in October to 23°C in mid-December (Fig. 29). The range in temperature was relatively small within any one field trip, never exceeding 4.2C° (Table 1). Thus, organisms living in coastal waters including the lower portions of the Gambia River could expect an annual thermal range of 12C° occurring in two distinct seasons. The cooler temperatures effectively exclude many truly tropical marine sesil species such as coral (Hyman 1940). Plankton and nekton are able to migrate with the oceanic currents, while benthos cannot. Those organisms which are truly estuarine, and cannot tolerate high salinities, cannot migrate southward along the coast with the warm waters because they cannot leave the river. However, thermal extremes were not as great up-river as they were in the lower estuary (Table 1).

During the period of the year when cold water dominates the coastline (December through May), salinity, alkalinity, and pH all tended to increase (Fig. 29). Thus the cooler waters were also more saline and had a greater buffering capacity. The correlations between temperature and salinity, alkalinity, and pH among all four field trips were -.534, -.559, and -.655, respectively. The explanation for these high negative correlations lies in part with the total lack of runoff to dilute the seawater during the cool and dry months. Thus, higher salinities accompanied lower temperatures. The net effect was that a moderate degree of stress was placed on organisms living in the lower estuary during the cool and salty months of December through May. The rains of 1983 were extremely meager, creating even drier conditions than normal and raising salinities to match those of the coastal environment.

Chemical Characteristics

The concentrations of dissolved materials in the lower estuary zone was essentially the same as the coastal marine waters. The marine character of this region of the Gambia River produced a suite of chemical characteristics that were in sharp contrast to much of the rest of the river (Tables 8 to 12). In general, mean concentrations of dissolved materials were relatively constant among the four field trips, but the range within any one field trip was large (Fig. 29). Three different species of dissolved nutrients were measured on a routine basis in the Gambia River; soluble reactive silica, soluble reactive phosphorus, and soluble nitrate-nitrogen.

Soluble reactive silica concentrations in the lower estuary were dominated by the relatively low concentrations of the coastal ocean (Fig. 12). Mean silicon concentrations ranged from 0.85 to 1.76 mg SiO_2/L (Table 9). These were low in contrast to the other zones of the river where mean concentrations ranged from 4.0 to 15.4 mg/L (Table 12). The range of silica concentrations found within any one field trip was large during and just after the rainy season, but much smaller during the dry season (Fig. 29). Results from up-river showed that runoff and/or groundwater had much higher dissolved silicon concentrations that the primarily marine waters of the lower estuary zone. The occasional high dissolved reactive silica concentrations observed in the lower estuary during the rainy season were attributed to runoff entering the river from adjacent bolons. These occasional high silicon concentrations served to elevate the mean concentrations to almost double the levels observed during the dry season field trip (Table 9). Concentrations of dissolved reactive silica have important implications for growth of silica-requiring plank-

ton (Wetzel 1983). In fresh waters, especially lakes with long residence times, silicon concentrations can become low enough to suppress and/or limit algal growth (Schelske and Stoermer 1971, Kilham 1971). Evidently, the lower estuary zone of the Gambia River and most of the entire river never experienced silica-limited algal production. Minimum soluble reactive silica concentrations exceeded 1.0 mg/L in all cases but one (Table 9), and rates of *in situ* primary productivity were usually very low (Healey et al. 1985).

Soluble reactive phosphorus (SRP) concentrations in the lower estuary zone were the opposite of soluble silica. SRP concentrations in the lower estuary were greatly elevated from the intrusion of seawater compared to the low concentrations found in the more freshwater portions of the river (Table 10). Mean SRP concentrations in the lower estuary ranged from 19.6 to 24.8 mg PO_4-P/L among the four field trips, while the largest mean concentrations upriver was 8.5 mg/L. The range in SRP concentrations during each field trip was rather large, exceeding 10 mg/L in all cases but the rising waters field trip (Fig. 10).

Soluble reactive phosphorus is considered a key dissolved nutrient for all forms of aquatic plant growth. In most fresh waters SRP has been identified as the element which limits or controls the amount and/or rate of primary productivity (Lean 1973). Salt water, on the other hand, has high concentrations of SRP and it rarely serves as a limit to plant growth (Dugdale 1967). The lower estuary zone of the Gambia River displayed typical saltwater characteristics with high SRP concentrations, thus this element was almost certainly not a limiting factor for plant growth.

Soluble nitrate-nitrogen concentrations varied over a wide range throughout the Gambia River, and the lower estuary zone shared this charac-

teristic with the other zones (Table 8). Mean concentrations of nitrate among the four field trips varied from 7.7 to 54.5 μg NO_3-N/L. The ranges of soluble nitrate observed during each field trip were extremely large, usually going from the limit of analytical detection to over twice the mean (Fig. 29).

Nitrate concentrations in salt water entering the Gambia River from the coastal environment were relatively low, usually below 10 μg NO_3-N/L. The water entering the river from the mangroves on the ebbing tide was often stripped of all measurable nitrate; this accounted for the frequent extremely low concentrations. Water moving down the river into the lower estuary zone had much higher nitrate concentrations (Table 8), especially water from the adjoining upper estuary zone. Runoff from the upland regions of the Gambia River appeared highly enriched in nitrate because concentrations were up to one order of magnitude higher in the freshwater portion of the river during the rainy season compared to the dry season. This seasonal nitrate enrichment was observed in all portions of the river including the lower estuary zone. Mean concentrations increased from the early rainy season (rising water field trip) through the end of the flood (declining waters field trip) (Fig. 29). After the flood had fully passed through the entire river, nitrate values began to decline.

Particulate Materials

The Gambia River had relatively high concentrations of particulate materials which evidently originated from runoff, tidal entrainment of soft sediments, and tidal scouring of bolon banks. The concentrations of total phosphorus and total nitrogen were relatively high in the lower estuary zone compared to the rest of the river (Tables 11 and 12). During all but the flood

stage field trip, mean total phosphorus concentrations were the highest or second highest of all the zones in the river. The same was true for total nitrogen (Table 12).

Total phosphorus and total nitrogen concentrations were composed almost entirely of organic phosphorus and nutrients, probably particulate organic forms (Fig. 29). Similar to the soluble nutrients, total nitrogen and phosphorus showed little seasonal variation in comparison to large ranges observed within one field trip. The correlations between suspended solids and total nitrogen and total phosphorus were large (.816 and .810, respectively). These results further suggested that most of what was measured as total nitrogen or total phosphorus was particulate nitrogen or particulate phosphorus. Microscopic examination of bacteria and algae samples showed a large amount of small plant detritus in both lower and upper estuary samples (Healey et al. 1985).

The suspended solids results were very similar to the total nitrogen and phosphorus results (Fig. 29). A large range was encountered during each field trip while the variation in means among three of the four field trips was not large. For example, mean suspended solids concentrations changed from 54 µg N/L on the first field trip to 33 µg N/L by the third field trip (Fig. 29). On the last field trip, the mean increased to 175 µg N/L, a result of several very high concentrations.

Suspended solids concentrations in the Gambia River were not especially high compared to other rivers (Maybeck 1982). The most evident aspect of the suspended solids results was the occasional periods of extremely high concentrations. This was observed in the lower estuary zone with the mean concentration for the last field trip between three and five times the mean

concentrations from the other field trips. Local fishermen suggested that high suspended solids events (observed as high turbidity) almost always accompanied spring tides, when tidal currents were at a maximum.

Chlorophyll concentrations in the lower estuary zone were relatively high compared to the other portions of the river; the mean concentration of chlorophyll in the lower estuary zone was always the second highest mean concentration of all the zones (Table 16). Chlorophyll concentrations showed some seasonal pattern with elevated values during the dry portion of the year and somewhat lower concentrations during the end of the rainy season (Fig. 29). Similar to the suspended solids results, chlorophyll values had large ranges within each of the four field trips in comparison to the overall annual range. The plant material flowing out of the mangrove bolons served to somewhat confound the chlorophyll results. Unlike the open ocean, high levels of chlorophyll or fluorescing materials are not necessarily phytoplankton. Thus the organic detritus entering the river on ebb tides was probably a major component to the computed chlorophyll concentrations. The correlation between suspended solids and chlorophyll was somewhat low (.450), suggesting that much of the suspended material observed in the lower estuary did not originate from plants.

Analysis of Variance Inferences

The experimental design used in this study allowed the investigation of several research hypotheses by ANOVA. The Latin Square sampling program provided the framework for testing several questions which were addressed through statistical techniques. These questions are: Were there differences in the mean value of each variable measured when the samples were collected at different stations across the river? at different transects along the river?

at different depths in the water column? or at different times of the day and stage of the tides?

In statistical terms, the ANOVA was used to test for significance of the main effects of station, transect, depth, and tide/time of day. The ANOVAs were conducted in a univariate mode, or one variable at a time. Results were considered statistically significant only if they had a probability of occurring by chance of less than 1% (.01). The somewhat conventional value of 5% (.05) was not used because over 20 ANOVAS per field trip per zone were conducted; by simple random chance at least one of each main effect tested would be statistically significant in at least one of the more than 20 ANOVAs.

The ANOVA results are summarized in Tables 18 to 21. Each table presents the results of the analyses for one field trip. The conclusions from the Latin Square ANOVAs were that tide-time of day and station location had significant effects on most of the variables for most of the field trips. The tide-time of day effect was significant in approximately 2/3 of the 56 ANOVAs conducted (14 variables x 4 field trips for each variable). Thirty six of the 56 F-tests for tide-time of day were statistically significant at the 1% probability level. The only variables which were not highly affected by the tide-time of day main effect were phaeopigment, soluble nitrate-nitrogen, and total phosphorus. The results were very similar for the stations' main effect; 33 of the 56 main effects were significant at the 1% probability level. Salinity and total phosphorus were the only two variables which did not vary significantly among the four stations on each transect.

Ecologically, the inference from these ANOVA results showed that the time of the day (day or night) and/or the phase of the tide (flood or ebb) were very important factors in determining the concentration variables mea-

TABLE 18. Summary of Greco-Latin Square Analysis of Variance for the rising water season in the lower estuary zone.

Variable	Transect	Station	Depth	Time/Tide	LF	Miss
Temperature (C)	**	*	**	**	na	0
Conductivity at 25C						32 na
Salinity (0/00)	**	*	**	**	na	0
Dissolved Oxygen (mg/L)	**	**	**	**	na	0
Dissolved Oxygen (% Sat.)	**	**	**	**	na	0
Chlorophyll <u>a</u> (μg/L)				**		0
Phaeopigments (μg/L)		**		*	*	0
pH	**				**	0
Alkalinity (mg/L $CaCO_3$)	**	*	*	**		0
Suspended Solids (mg/L)	*	**	**	*	**	1
SiO_2 (mg/L)	**	**	*	**	**	0
PO_4-P (μg/L)			*	**	**	0
NO_3-N (μg/L)	**	**	**		**	0
NH_3-N (μg/L)						32 na
Total Phosphorus (μg/L)	*	*	*	*	*	1
Total Nitrogen (μg/L)	**	**	**	**	**	2

TABLE 19. Summary of Greco-Latin Square Analysis of Variance for the flood season in the lower estuary zone.

Variable	Transect	Station	Depth	Time/Tide	LF	Miss
Temperature (C)	**	*	**	**		1
Conductivity at 25C						32 na
Salinity (0/00)				**	**	0
Dissolved Oxygen (mg/L)	**	**	**			0
Dissolved Oxygen (% Sat.)	**	**	*			0
Chlorophyll <u>a</u> (μg/L)	**	**	**	**		0
Phaeopigments (μg/L)			**	**		0
pH	**	**	*	**		0
Alkalinity (mg/L $CaCO_3$)	**	**		**		0
Suspended Solids (mg/L)	*	**	**	**	**	0
SiO_2 (mg/L)		**		**		0
PO_4-P (μg/L)				**	*	0
NO_3-N (μg/L)		**		**	**	0
NH_3-N (μg/L)						32 na
Total Phosphorus (μg/L)		*	**	**	*	1
Total Nitrogen (μg/L)						0

TABLE 20. Summary of Greco-Latin Square Analysis of Variance for the declining water season in the lower estuary zone.

Variable	Transect	Station	Depth	Time/Tide	LF	Miss
Temperature (C)	**	**	**	**	**	2
Conductivity at 25C						32 na
Salinity (0/00)				**	**	2
Dissolved Oxygen (mg/L)						2
Dissolved Oxygen (% Sat.)						2
Chlorophyll a (μg/L)		**		**	**	2
Phaeopigments (μg/L)					**	2
pH	**		**	**	**	2
Alkalinity (mg/L $CaCO_3$)						2
Suspended Solids (mg/L)					**	3
SiO_2 (mg/L)	**	**		**		2
PO_4-P (μg/L)		**		**	*	2
NO_3-N (μg/L)					**	2
NH_3-N (μg/L)						32 na
Total Phosphorus (μg/L)						5 na
Total Nitrogen (μg/L)						4 na

TABLE 21. Summary of Greco-Latin Square Analysis of Variance for the dry season in the lower estuary zone.

Variable	Greco-Latin Square Analysis					
	Transect	Station	Depth	Tide	LF	Miss
Temperature (C)	**	**	**	**	**	0
Conductivity at 25C						32 na
Salinity (0/00)				**		0
Dissolved Oxygen (mg/L)		**		**	**	0
Dissolved Oxygen (% Sat.)		**		**	**	0
Chlorophyll a (μg/L)	**	**		**	**	0
Phaeopigments (μg/L)	**	**	**	*		0
pH		**		**	**	0
Alkalinity (mg/L $CaCO_3$)		**		**	**	0
Suspended Solids (mg/L)	**	**	**	**	**	0
SiO_2 (mg/L)		**				0
PO_4-P (μg/L)		**		**		0
NO_3-N (μg/L)						0
NH_3-N (μg/L)						32 na
Total Phosphorus (μg/L)						0
Total Nitrogen (μg/L)	**	**	*	**	**	0

sured in the lower estuary zone. For example, salinity levels were almost always higher on flooding tides compared to ebbing tides. Likewise, water temperatures were cooler on flooding tides during the last two (cold season) field trips.

The same general inference held true for station location. In particular, those samples collected along the edges of the river over the shallow mud flats near the mangrove bolons were usually different from those samples collected in mid-river. Soluble reactive silica values were invariably lowest along the North bank of the Gambia River, but highest along the south bank. Per cent saturation of dissolved oxygen was almost always higher at the edges of the river than in the center of the river (Appendix 1).

The effect of sampling at different transects along the river was not as large as either the station or time-tide factors (Tables 18 to 21). Twenty three of the 56 F tests were significant at the 1% probability level. Those variables which were affected by transect location were water temperature, dissolved oxygen, chlorophyll, pH, alkalinity, soluble reactive silica, and total nitrogen. Variability introduced by sampling at different transects did not follow consistent patterns as was the case for time-tide and station. Rather, on some field trips the up-river transects had lower values than the down-river transects, while on the next field trip the opposite trend was observed (see pH, for example, in Appendix 1).

The effect of collecting samples at different depths was very minimal with only 17 of the 56 individual F-tests significant at the 1% probability level (Tables 18 to 21). The only variables which were affected by depth were water temperature, phaeopigments, suspended solids, and total nitrogen. Ecologically, these results were meaningful only for the

water temperature and suspended solids variables. Suspended solids concentrations were higher in near-bottom samples for three out of the four field trips (Appendix 1). Surface water temperatures tended to be either warmer during the warm season or colder during the cool season than the rest of the water column.

The Latin Square ANOVAs had a variety of assumptions which must be met. ANOVA in general requires several assumptions which include normally distributed data, homoscedasticity, independence of error terms, and additive effects (Sokal and Rohlf 1981). The Latin Square ANOVAs have the further requirement that there is no interaction among the main effects (Winer 1971, Netter and Wasserman 1974). While all of these assumptions were not tested for all variables, the important ones were tested for all the variables. The distribution of the variables was checked for each zone for each cruise by descriptive statistics. In general, excessive skewness or kurtosis were not observed in all but a few variables with large ranges such as suspended solids. The lack or presence of interaction among the main effect or blocking variables was tested more directly by the Greco-Latin ANOVA. Replicate samples collected in each cell allowed the test for lack-of-fit to the Latin Square statistical model. The results showed that about 40% (24 out of 56) of the Latin Square models had some interaction among blocking variables. Only about half of these significant lack-of-fit F-tests indicated sufficient magnitude of the interactions to invalidate the entire ANOVA (Netter and Wasserman 1974). Thus, while the Latin Square model could not be used without reservations, it was generally an apt and extremely useful analytical tool.

UPPER ESTUARY

Physical Characteristics

The upper estuary zone extended from the highly saline waters of the lower Gambia River to the freshwater-saltwater interface. Geographically this zone extended from approximately Mootah Point (25 km upstream) to Kuntaur (250 km upstream). The upstream boundary of the upper estuary zone shifted throughout the year because of the annual flood. This flood pushed the extent of saltwater penetration downstream to approximately Bai Tenda (150 km upstream). Because the boundary shifted with the seasons, the upstream limit of the upper estuary zone was defined as the maximum upstream penetration of salt water (0.5 ppt) which was at Kuntaur for the 1983-84 dry season.

The upper estuary zone could be described as truly estuarine in that this segment of the river has a distinct salinity gradient and extensive tidal characteristics. The channel is much narrower than the lower estuary, but the very flat topography allows the movement of tidal waves over 500 km upstream. Thus, the entire upper estuary is under the influence of tides with the same semi-diurnal pattern that existed at the river's mouth at Banjul. The tidal amplitude decreases to about 1.25 m in the upper estuary zone from close to 2.0 m near Banjul. The tidal currents are especially strong during the spring tides and often exceed 3.0 km/hr. Tidal waves propagate the full length of the bolons as well as along the river.

The morphometry of the river included a rather deep central channel that occupied most of the full width of the river. The river banks descended steeply from the edge of the mangroves to a depth of between 8 and 10 m. The central portion of the river channel was up to 18 m deep at high tide. The numerous mangrove bolons were also rather deep, often over 5 m deep at the

point where they intersected the river. These bolons ranged from 2 to 15 km in length.

The width of the river at this location changed considerably during the annual floods because of the extremely flat terrain adjacent to the river. The average width of the river channel at this location was approximately 500 m. The average water depth during the July field trip was 15 m and this increased about 1 m during the October field trip when the flood was at the annual maximum. The bottom sediment was composed primarily of soft silty muds.

The upper estuary zone primary sampling site was located near Bai Tenda, approximately 30 km up the river from the proposed salinity barrage at Balingho. This site was located in a region of the river that has many meandering and sometimes interconnected bolons that allows tidal water to pass into the mangrove forests. These tidal flats are formed by sulphidic muds and contain high levels of iron pyrites and sulfur.

Aquatic Characteristics

Over the course of the study, the chemical composition and aquatic characteristics of the river water underwent, in most cases, greater seasonal changes in the upper estuary than in the other zones. Most of the changes occurred as a result of the annual flood. The seasonal trend of most of the physical and chemical variables can be explained through a direct or inverse relationship to salinity and suspended solids trends which are affected by freshwater runoff.

The salinity of the upper estuary varies inversely with the discharge of fresh water. During July 1983, prior to an increase in the river's discharge at Bai Tenda, a salinity of 13.7 ppt was the maximum annual mean observed at

this location. During the October 1983 field trip, when the river was in flood stage, the minimum mean for the year of 0.2 ppt salinity or a mean conductivity of 785 μmhos cm^{-1} (25°C) was observed. During the flood, a salinity of 0.5 ppt was found near Bai Tenda about 150 km upstream (Fig. 5). This was the only time during the study that the primary sampling site for the upper estuary contained fresh water. In December the freshwater discharge was declining, hence the salinity at Bai Tenda increased, reaching a mean value of 2.2 ppt. In March the mean salinity was 11.2 ppt, which was slightly lower than in July. Following this field trip until the next rainy season, the salinity increased and most likely surpassed the July 1983 value because of the record low rainfall in 1983.

The salt water of the river, when compared to the river's fresh water, has a greater alkalinity or acid neutralizing capacity due to its abundant concentration of carbonate species and other ions. At Bai Tenda this can be seen by comparing the extremes in alkalinity. When the water was saline the maximum mean value of 72.7 mg/L $CaCO_3$ was observed, and when it was fresh a minimum mean value of 2.71 mg/L $CaCO_3$ was measured. There was very high correlation between salinity and alkalinity (.903) for all the samples taken over the course of the study; hence the seasonal trend in alkalinity is greatly influenced and follows the same seasonal trend as salinity (Fig. 30).

The thermal regime of the upper estuary zone appeared to be a combination of upstream and lower estuary water temperatures. As mentioned above, the lower estuary derived its thermal characteristics primarily from the coastal oceanic environment. The freshwater portions of the river were primarily controlled by air temperatures which in turn were driven by the annual pattern of rainfall. The upper estuary zone appeared to correspond to both

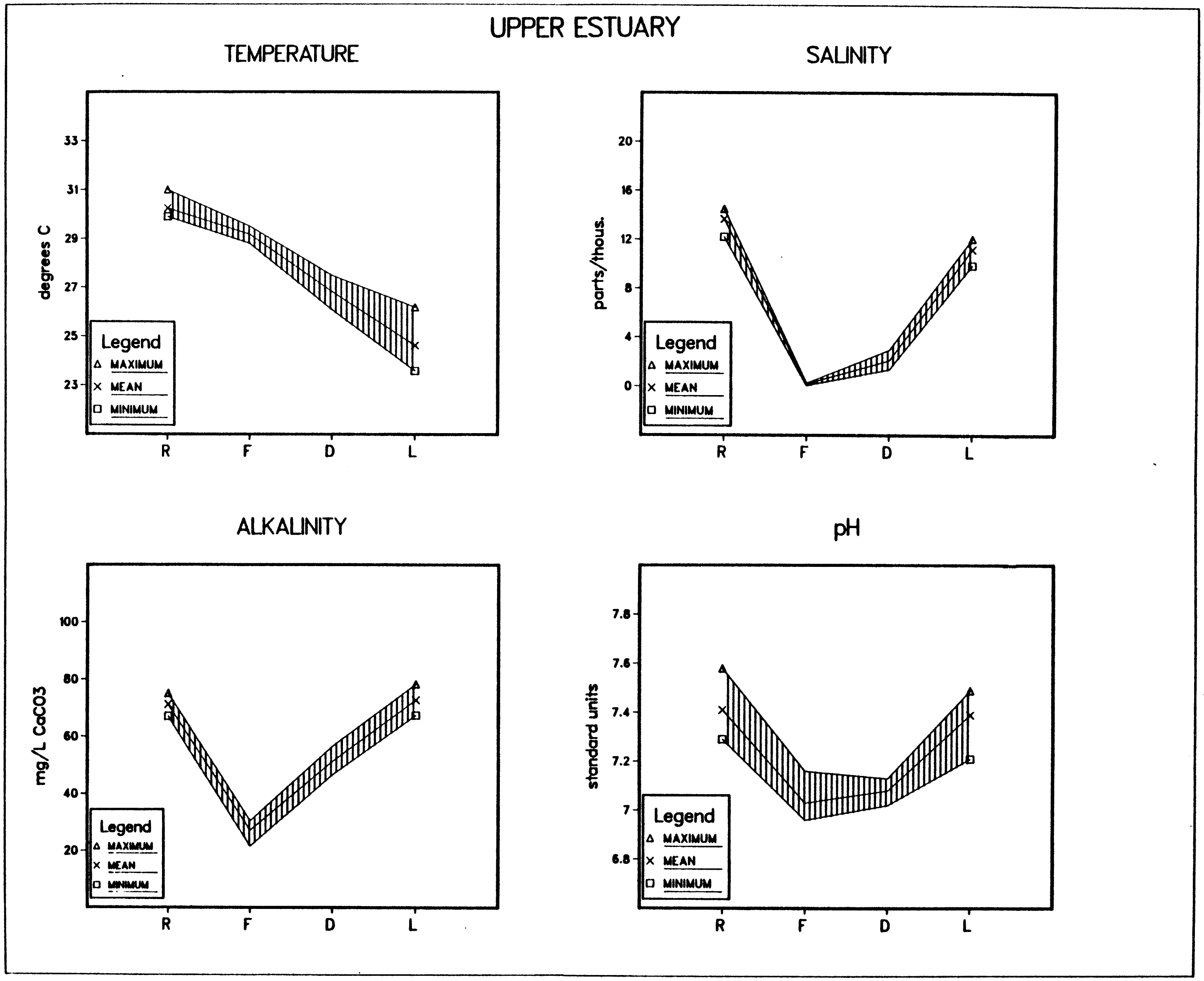

FIGURE 30. Means and ranges of physical and chemical variables for the upper estuary zone.

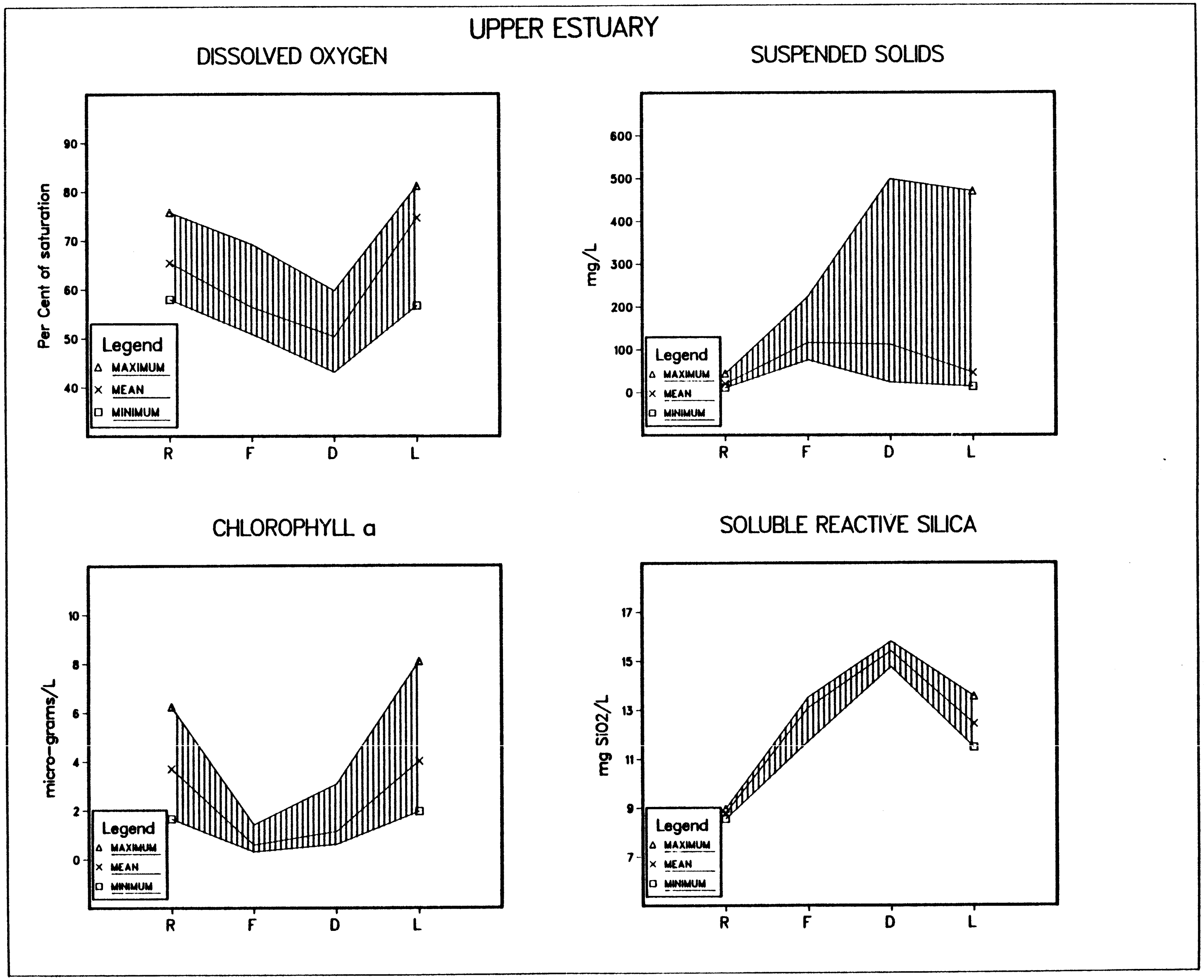

FIGURE 30. (continued).

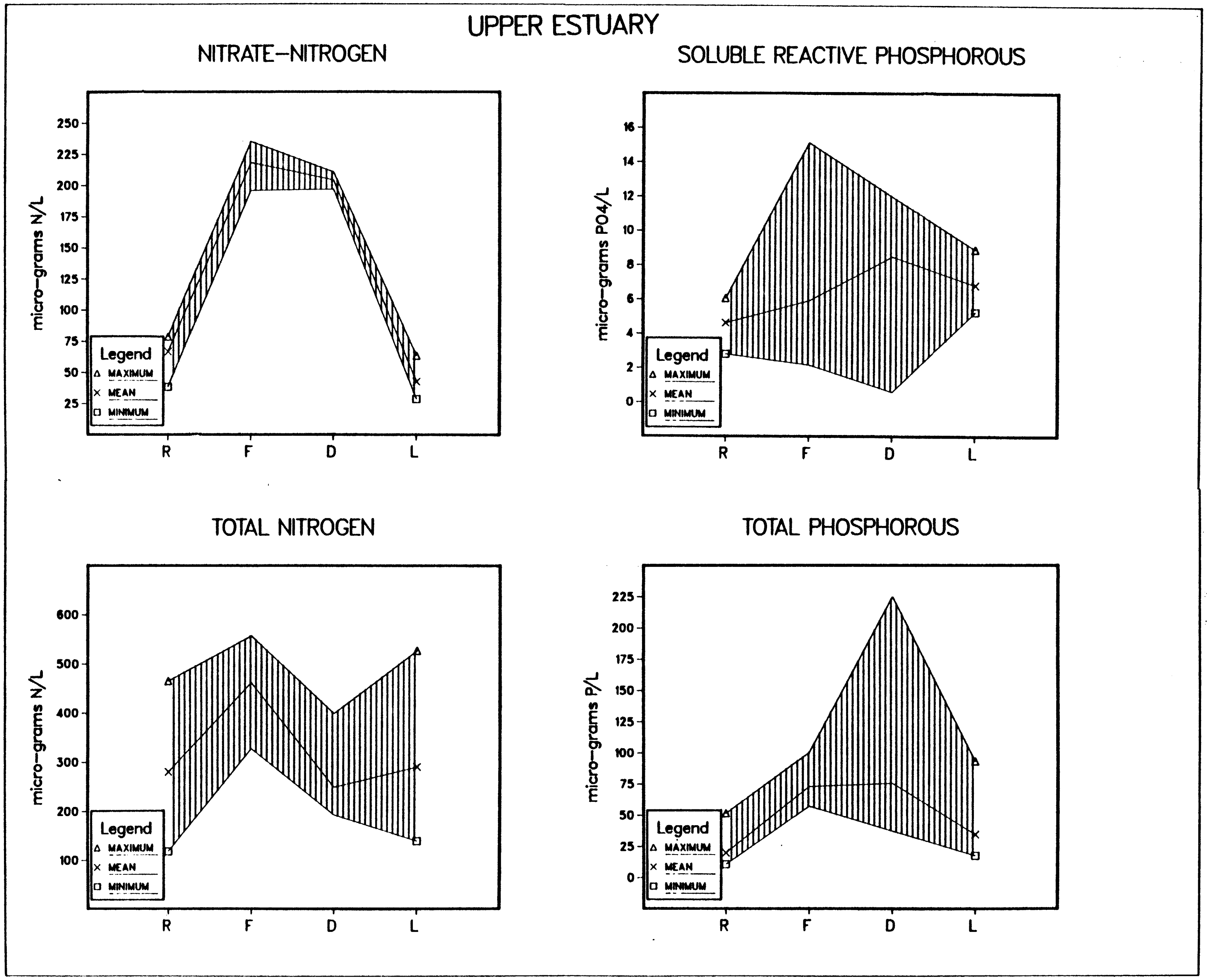

FIGURE 30. (continued).

the influx of salt water with the tide and downstream flow of fresh water. Figure 30 shows that the water temperatures were maximal in the upper estuary zone during the rising waters period (July) when coastal waters were warm and runoff from the annual flood had just begun. As runoff increased, water temperatures fell and continued to fall for the next 9 months. During the latter stages of the annual flood, water temperatures apparently fell as both the air temperatures decreased and cooler ocean water entered the river. But, in the low water period (March), air temperatures significantly increased from December. However, the water temperatures in the upper estuary did not increase with the air temperatures. Evidently the cool coastal ocean waters had a significant impact on the low water season in the upper estuary zone.

The pH at Bai Tenda showed the same seasonal trend as salinity and alkalinity. pH was highly correlated with salinity (.955) and alkalinity (.888). Generally, the salt water in the Gambia River showed an increase in pH with salinity; however, pH values in an area centered around Bai Tenda were much lower than expected, hence variables other than salinity affected the pH at this location. Dissolved oxygen saturation had a high positive correlation with pH (.736) and pH had a high negative correlation with suspended solids (-.540).

Chemical Characteristics

The nutrients silica, nitrate, and soluble reactive phosphorus followed an opposite seasonal trend to that of salinity. Their concentrations increased rapidly following the onset of the annual rains. Nitrate-nitrogen reached a maximum mean concentration in the upper estuary during the rising (October) field trip, while phosphate and silica reached maximum mean concentrations during the flood (December) field trip. All the soluble nutrients

showed highly significant negative correlations with salinity. Nitrate showed the highest negative correlation (-.947), with silica and phosphate -.863 and -.576, respectively. Because the upper estuary zone undergoes large salinity changes over the course of the year, there would be additions of phosphorus and dilutions of silica by the salt water.

Soluble reactive silica concentrations in the upper estuary zone of the Gambia River were controlled by the annual cycle of saltwater intrusion (Fig. 30). Gambian coastal waters contain very little silica in contrast to the fresh water of the river (Table 9). As a result, when salt water intrudes greater distances during the dry season, soluble silica concentrations drop in relation to the salt water invasion. This produces a definite seasonal pattern of silica concentrations in the upper estuary zone (Fig. 30). At the upper estuary sampling site at Bai Tenda, silica concentrations reached their annual nadir just as the flood began. Concentrations increased during the flood season until they peaked in December. The mean concentrations increased from just below 9 mg SiO_2/L to over 15 mg SiO_2/L. After the annual flood had passed, concentrations began to decrease, but remained relatively high through the low water field trip (March). Evidently some sources of silica continued to enter the river during the dry season despite the intrusion of low silica salt water. Figure 30 shows that the range of concentrations within any one field trip was small compared to the annual range.

Soluble reactive phosphorus (SRP) concentrations also showed a noticeable seasonal pattern, again as a result of the differences between salt- and freshwater concentrations. In the case of SRP, saltwater concentrations are much higher than saltwater values. The annual pattern in the upper estuary in SRP resulted from the flushing of high phosphate salt water by low phosphate

fresh water. The pattern was similar to soluble silica (Fig. 30), with the lowest mean concentration during the rising water field trip and highest during the declining water field trip. Based on only a dilution of fresh water with salt water, the observed annual pattern should not have occurred. Rather, SRP concentrations should be lowest during the annual flood and highest for the low water field trip. Table 10 shows that concentrations were lowest just as the annual flood began. But, Healey et al. (1985) showed that the period of highest phytoplankton growth and biomass was during the rising water field trip. Thus, high utilization of SRP for algal growth may have served to reduce SRP concentrations despite intrusion of high phosphate salt water. However, the trend in annual means is small in comparison to the range of phosphate concentrations observed in the upper estuary zone during any one field trip (Fig. 30).

The annual trend of soluble nitrate-nitrogen (NO_3) was most clearly tied to the flood. Figure 30 shows the decided increase and decrease in NO_3 concentrations during the flood and declining waters field trip. The mean NO_3 concentration increased from about 67 μg NO_3-N/L during the rising water field trip to over 218 μg NO_3-N/L in October and dropped to less than 43 μg NO_3-N/L in March (Table 8). The factors controlling this annual trend are tied directly to the changes induced by the annual flood. Runoff from throughout the Gambia River basin is high in NO_3 concentrations. As the annual flood begins, a surge of high NO_3 water moves down the river, which can be traced from the headwaters to the lower estuary zones. That surge of water is noticeable in the upper estuary zone as salinity rapidly falls during the beginning of the flood. As the flood waters recede, nitrate concentrations fall in the upper estuary zone with the intrusion of low-NO_3 sea water. There are some fluctua-

tions in the concentrations of NO_3 within each field trip; these were attributed to the affect of high-NO_3 water draining out of the bolons on ebbing tides. But, the within-field-trip variance in NO_3 concentrations was small compared to the seasonal changes.

Particle Materials

Throughout the course of the study, suspended solids measured in the upper estuary zone directly followed the river's discharge, which is also indicated by the negative correlation between suspended solids and salinity (-.518). The lowest mean value of 20.3 mg/L was observed in July, prior to the annual flood. As the flood began, suspended solids were flushed into the system and, due to increased flow, bottom sediments were suspended yielding a maximum mean suspended solids value of 166.4 mg/L during the flood stage in October. The upper estuary sampling site was in the middle of an area of high suspended solids which extended from near Tendaba to around Kudang. During the December field trip the mean suspended solids value declined only slightly to 111.6 mg/L. With the decreased flow in March the mean suspended solids declined to 45.8 mg/L.

Total phosphorus and organic phosphorus followed the same seasonal trend as suspended solids. Total phosphorus, which is strongly dominated by the organic fraction, was highly correlated with suspended solids (.936). This result suggests that most of the phosphorus was in the particulate form. Total nitrogen followed the same seasonal tend as nitrate-nitrogen. This is probably because the organic fraction, which is determined by subtracting the nitrate-nitrogen and ammonic nitrogen (which when measured was very low), changed very little throughout the season; hence the changes in nitrate-nitrogen predominantly influenced the changes in total nitrogen.

Dissolved oxygen and chlorophyll a showed a seasonal trend opposite to that of suspended solids. Hence they showed a negative correlation with suspended solids (dissolved oxygen saturation -.447, chlorophyll a -.388) and a high positive correlation with each other (.702). Phaeopigments were highly correlated with suspended solids (.781). These relationships between suspended solids, dissolved oxygen, chlorophyll a, and phaeopigments may be explained by the suspended solids reduction of the photogenic zone. As the turbidity due to suspended solids increased the photogenic zone decrease, photosynthesis decreased yielding smaller phytoplankton biomass and hence lower chlorophyll a while allowing the phaeopigments from dead algae to increase (Healey et al. 1985).

Analysis of Variance Inferences

The Latin Square experimental design used in the upper estuary zone as well as the other sampling locations provided statistics to test several research hypotheses. The hypotheses tested were the same as those of the lower estuary which included the effects of station location, depth, and tide/time-of-day. Over the course of the four field trips, 60 ANOVAs were conducted using upper estuary results. The individual ANOVA results are presented in Appendix 1, with the overall findings presented in Tables 22 to 25. Each table presents the results of the analyses for one field trip. The conclusions were similar to the lower estuary results in that the tide/time-of-day main effect was clearly the dominant factor in the upper estuary. This main effect was significant (at the 1% probability level) for 36 of the 60 ANOVAs, or approximately 60% of the analyses. Throughout the course of the study, all variables changed significantly among different stages of the tide and time-of-day was chlorophyll. There was, however, a decided seasonal pattern.

TABLE 22. Summary of Latin Square Analysis of Variance for the rising water season in the upper estuary zone.

Variable	Transect	Station	Depth	Time/Tide	LF	Miss
Temperature (C)						0
Conductivity at 25C						1
Salinity (0/00)						0
Dissolved Oxygen (mg/L)						0
Dissolved Oxygen (% Sat.)			*	**		1
Chlorophyll a (μg/L)			*	**		1
Phaeopigments (μg/L)						0
pH						0
Alkalinity (mg/L $CaCO_3$)						0
Suspended Solids (mg/L)		*	**			2
SiO_2 (mg/L)						2
PO_4-P (μg/L)						2
NO_3-N (μg/L)						2
NH_3-N (μg/L)						63 na
Total Phosphorus (μg/L)						3
Total Nitrogen (μg/L)						2

TABLE 23. Summary of Greco-Latin Square Analysis of Variance for the flood season in the upper estuary zone.

Variable	Transect	Station	Depth	Time/Tide	LF	Miss
Temperature (C)				**		0
Conductivity at 25C	*	**		**	**	0
Salinity (0/00)						24 na
Dissolved Oxygen (mg/L)				**		0
Dissolved Oxygen (% Sat.)			**	**		0
Chlorophyll a (μg/L)						1
Phaeopigments (μg/L)	**		*	**	**	1
pH			**	**		0
Alkalinity (mg/L $CaCO_3$)				**		0
Suspended Solids (mg/L)			*	**	*	0
SiO_2 (mg/L)				**		0
PO_4-P (μg/L)				**		0
NO_3-N (μg/L)				**		0
NH_3-N (μg/L)						1
Total Phosphorus (μg/L)			*	*		3
Total Nitrogen (μg/L)						2

TABLE 24. Summary of Greco-Latin Square Analysis of Variance for the declining water season in the upper estuary zone.

Variable	Transect	Station	Depth	Time/Tide	LF	Miss
Temperature (C)	**			**	**	0
Conductivity at 25C			**	**	**	1
Salinity (0/00)			**	**	**	0
Dissolved Oxygen (mg/L)	**		**	**	**	0
Dissolved Oxygen (% Sat.)	**		**	**	**	0
Chlorophyll _a_ (μg/L)						0
Phaeopigments (μg/L)		*	**		**	0
pH				**		0
Alkalinity (mg/L $CaCO_3$)			**	**		0
Suspended Solids (mg/L)	*	**	**	*	**	0
SiO_2 (mg/L)			**	**		0
PO_4-P (μg/L)			*	**		0
NO_3-N (μg/L)				**		0
NH_3-N (μg/L)						0
Total Phosphorus (μg/L)	*	*	**		**	0
Total Nitrogen (μg/L)		**		**		0

TABLE 25. Summary of Greco-Latin Square Analysis of Variance for the dry season in the upper estuary zone.

Variable	Transect	Station	Depth	Time/Tide	LF	Miss
Temperature (C)	**	*	**	**	**	0
Conductivity at 25C		*	**	**		0
Salinity (0/00)		*	**	**		0
Dissolved Oxygen (mg/L)	**	**		**	**	0
Dissolved Oxygen (% Sat.)	**	**		**	**	0
Chlorophyll _a_ (μg/L)				*		0
Phaeopigments (μg/L)						0
pH		**		**	**	0
Alkalinity (mg/L $CaCO_3$)		**	**	**	**	0
Suspended Solids (mg/L)				*		0
SiO_2 (mg/L)		**	**	**		0
PO_4-P (μg/L)	*		**	**	**	0
NO_3-N (μg/L)		**	**	**		0
NH_3-N (μg/L)						32 na
Total Phosphorus (μg/L)			**	**		2
Total Nitrogen (μg/L)			*	**		2

Table 22 shows that only two variables (chlorophyll and dissolved oxygen) changed significantly with tide and time-of-day during the rising waters field trip (July). In contrast, twelve out of fifteen variables changed significantly during the low water field trip (March).

The ecological inference from these results was generally the same as in the lower estuary; that tidal flushing generated sufficient mixing to alter the conditions of the river water. The mechanism responsible for the changes appeared different between the lower and upper estuary. In the former, influx of coastal waters changed conditions in the Gambia River. In the upper estuary, the surging of water between the main river channel and the bolons generated the changes in water quality. Nutrient conditions were especially altered as water drained out of the mangrove bolons and into the river. This concept is discussed in more detail below.

None of the other three blocking variables (transect, station, and depth) yielded as many significant results as the tide/time-of-day variable. The effect of depth was confined to 20 of the 60 ANOVAs which showed a significant effect for this variable. Over the course of the 1-year study, the only variables that did not change significantly with depth were chlorophyll and total nitrogen. Again, there was a seasonal pattern with only one significant effect during the rising water field trip compared to eleven for the low water field trip. This pattern of results was attributed to the presence or lack of vertical stratification in the river during the flood versus dry season. High stream flows of the flood kept the river well mixed.

The other two blocking variables, station and transect location, had only minor roles in affecting the distribution of variables. Only seven and nine of the sixty ANOVAs showed significant effects for transect and station

location, respectively. Most of the significant effects were from the low water field trip (Table 25). The conclusion from these results is that the narrow and deep river channel was well mixed by the tides. The mixing action prevented both vertical and horizontal stratification in the river.

The analysis of the aptness of the Latin Square statistical model to the results from the Gambia River showed that 15 of the 60 (25%) ANOVAs had significant interaction. This result was similar to the lower estuary findings in that the general use of the sophisticated design was more than justified by the large reduction of the number of samples collected and processed.

MANGROVE BOLONS

The importance of the mangrove ecosystems to the ecology of the upper estuary zone became evident early in the Gambia River Basin Study. As a consequence, a separate investigation of mangrove ecosystems was carried out. The main purpose of the mangrove study was to determine the exchange of materials between the river and mangrove bolons in the upper estuary zone, as well as to characterize the dynamics within the bolons.

The mangrove ecosystems were very active biologically and, as a result, had a significant effect on most water quality parameters. These effects were investigated by the following experimental design: At two different phases of the tide (high water and low water) and two different times of the day (day and night), samples were collected in the middle of the main Gambia River channel and at up to five locations within a mangrove bolon. Samples were then compared at one location over time, or at one time among several locations. Net changes in the value of each water quality parameter emerged from these comparisons.

Physical Characteristics

The mangrove ecosystems of the Gambia River extend from the river's mouth to the extreme extent of saltwater penetration, about 250 km upstream, near Kuntaur. The mangrove forests along the Gambia River are composed of up to seven species of trees in three different genera (Twilley 1985). Each species has its own salt tolerance, thus the composition of the forests varies with distance upstream. Those near the ocean are somewhat stunted and sparse because of hypersalinity on the mud flats. The mangroves near the upstream limit of saltwater penetration grow only in small isolated clumps at the river's edge. The mangroves near Bai Tenda were the most luxuriant, growing in dense stands with stream-side specimens over 30 m tall; the primary sampling location for the mangrove study was among these luxuriant stands.

Along the Gambia River near Bai Tenda, mangroves typically border the bolons and main river channel. The bolons are extremely convoluted and up to 15 km long. Tidal scouring keeps the bolons relatively open, with channel depths from 1 to 5 m and widths 5 to 30 m. Narrow bolons are often totally overgrown by arching branches of *Rhizophora racemosa*.

The Bai Tenda area bolons are flushed twice per day by tidal waves that move so rapidly up them that a distinct surge can be observed. Currents generated by the tides occasionally slightly exceeded 1 m/s at the mouth of some bolons during spring tides. When water levels reached three fourths of high tide level or higher, the mud flats where the mangroves grow became inundated. Tidal ranges in the vicinity of the Bai Tenda varied from 1.5 m in the main river channel to about 1 m at the end of the bolons. The mangrove stands often extend several hundred meters back from the bolon bank. The bolons near Bai Tenda are so numerous as to produce a continuous forest that in some

places extends up to 3 km from the river. The mangrove forests were not continuous in the lower estuary zone because the salt pans or mud flats covered with hypersaline water caused numerous openings among them.

Aquatic Characteristics

The movement of Gambia River water into mangrove bolons caused a change in every physical and chemical characteristic. Some of these changes were very large and repeatable with every tidal cycle, while other changes were occasional. Results from the March (low water) field trip show changes in several variables among different stages of the tide at various locations in the bolon (Figs. 31-34). Water temperature generally decreased with distance in the bolon with an overall drop of about 2C° (Fig. 31). The exception was at low tide during the night when temperatures increased almost 4C°. These results are somewhat misleading because the low water night samples were collected less than 2 h after sunset. The elevated temperatures were probably a response to water lying on the warm mud flats throughout the late afternoon. Likewise, the declining temperatures of the day-time high tide were observed only a few hours after sunrise. In general, river water changed temperature as it moved into and out of the bolons. That change was tied to the air temperatures and phase of the tide with the time of day.

During March, salinities changed considerably between the bolon mouth and 2 km upstream (Fig. 31). Although March was the middle of the dry season, some freshwater seepage was evident from the salinity and alkalinity results. Flood tide salinities were generally higher at the bolon mouth and 2 km upstream compared to the middle sections of the bolon. Higher salinities at the bolon mouth were attributed to more saline water moving into the bolon from the main river channel. Higher salinities at the end of the bolon were proba-

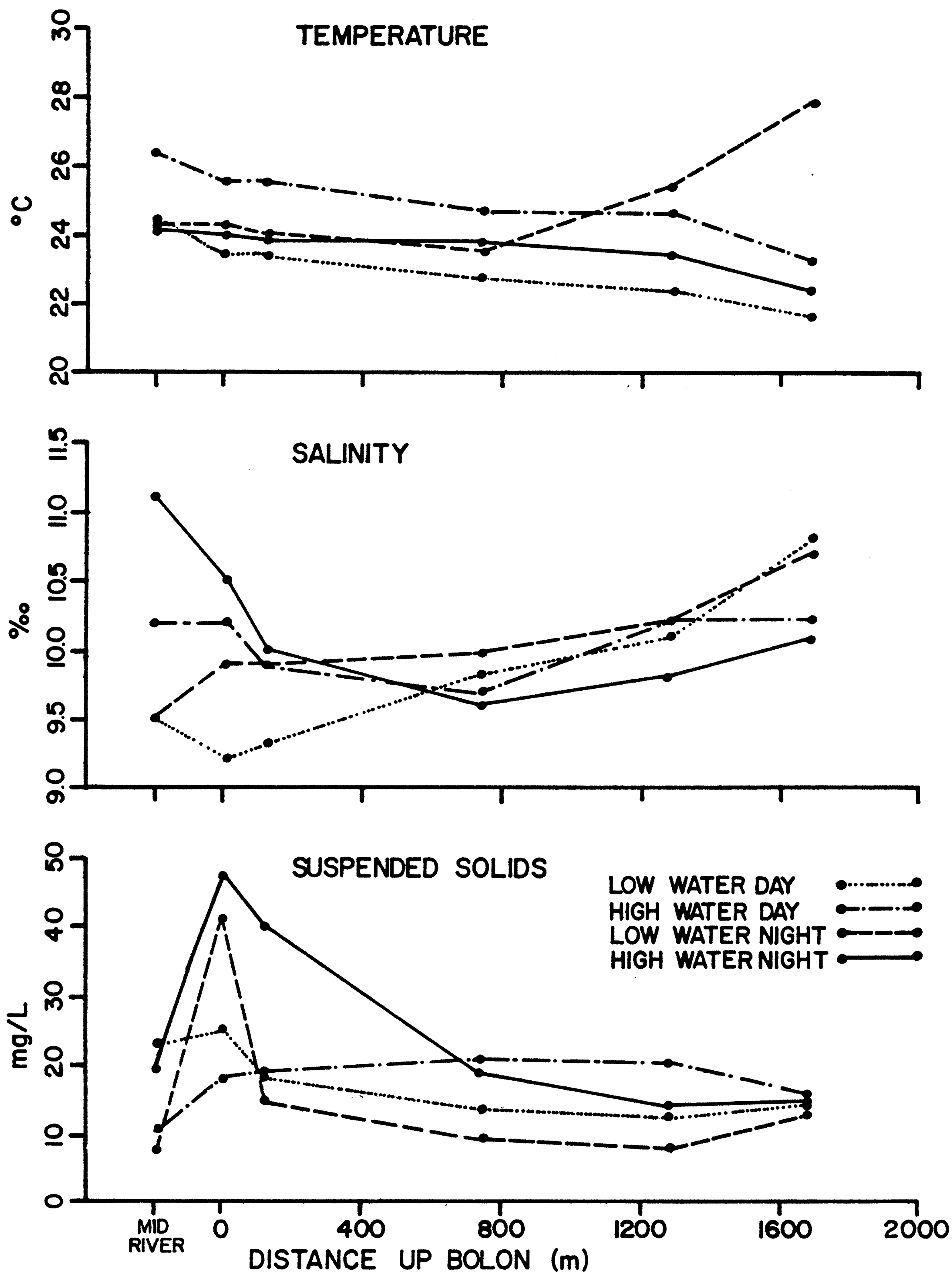

FIGURE 31. Changes in temperature, salinity, and suspended solids with distance up Bai Tenda bolon.

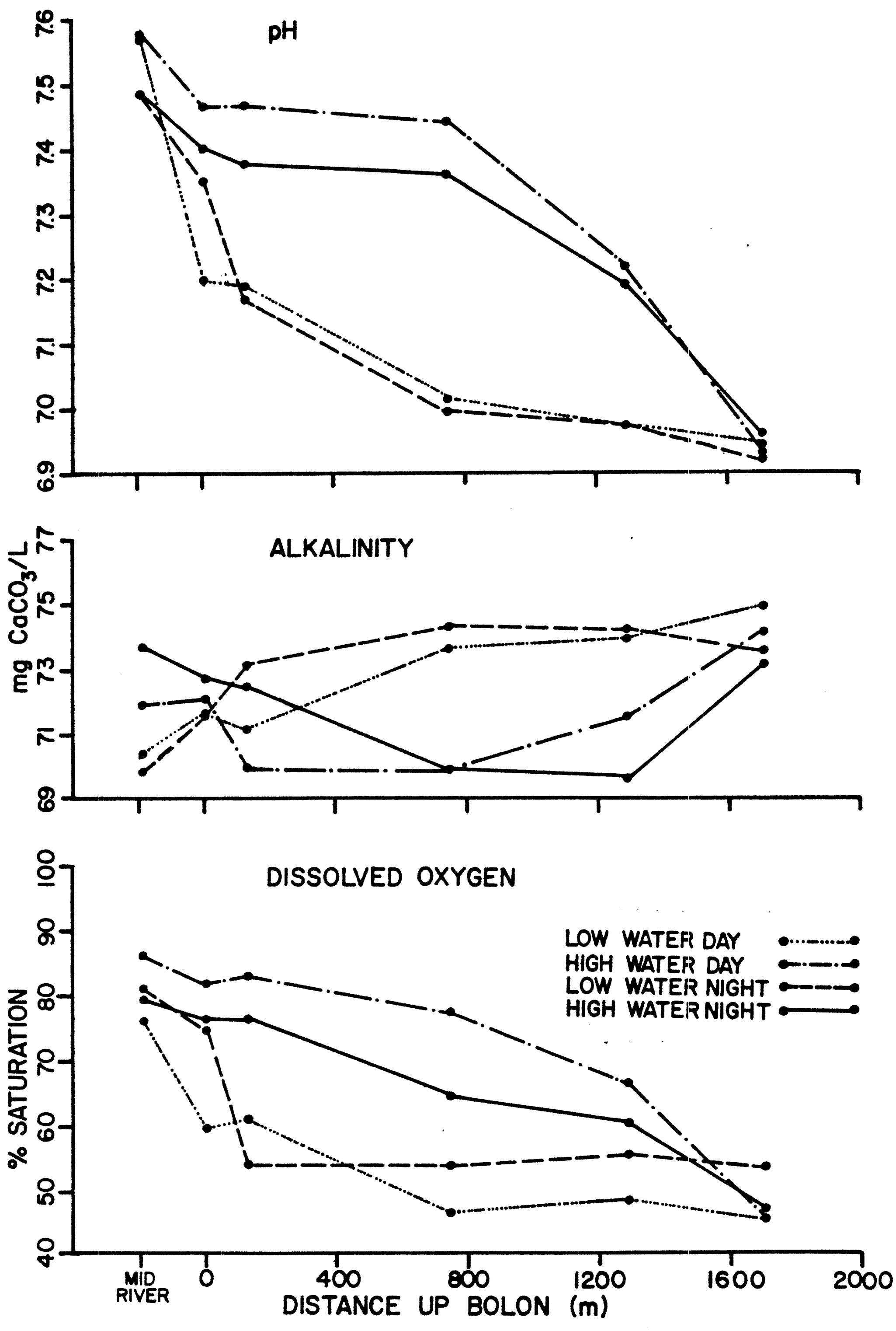

FIGURE 32. Changes in pH, alkalinity, and dissolved oxygen with distance up Bai Tenda bolon.

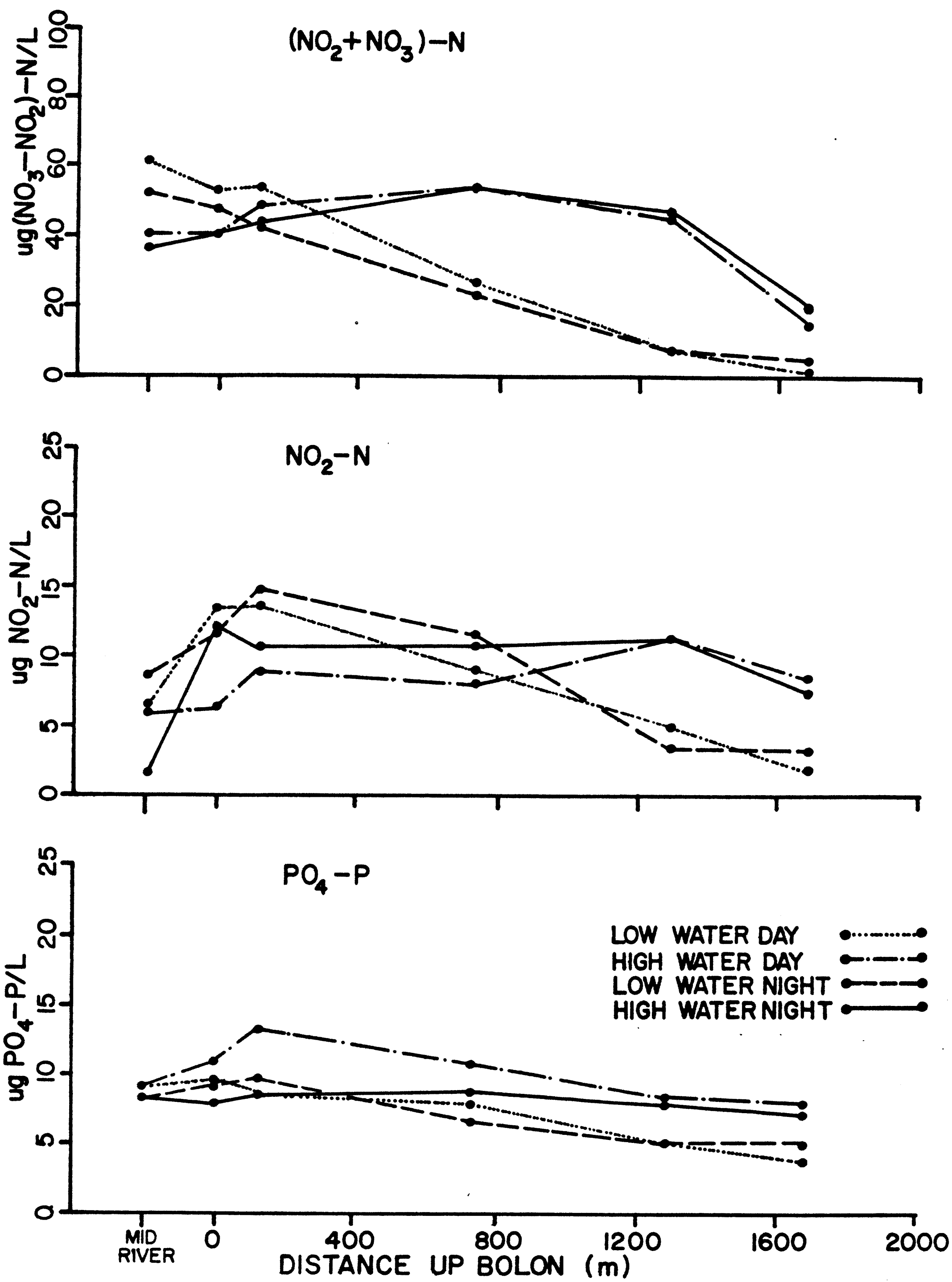

FIGURE 33. Changes in nitrate-nitrogen, nitrite-nitrogen, and soluble reactive phosphorus with distance up Bai Tenda bolon.

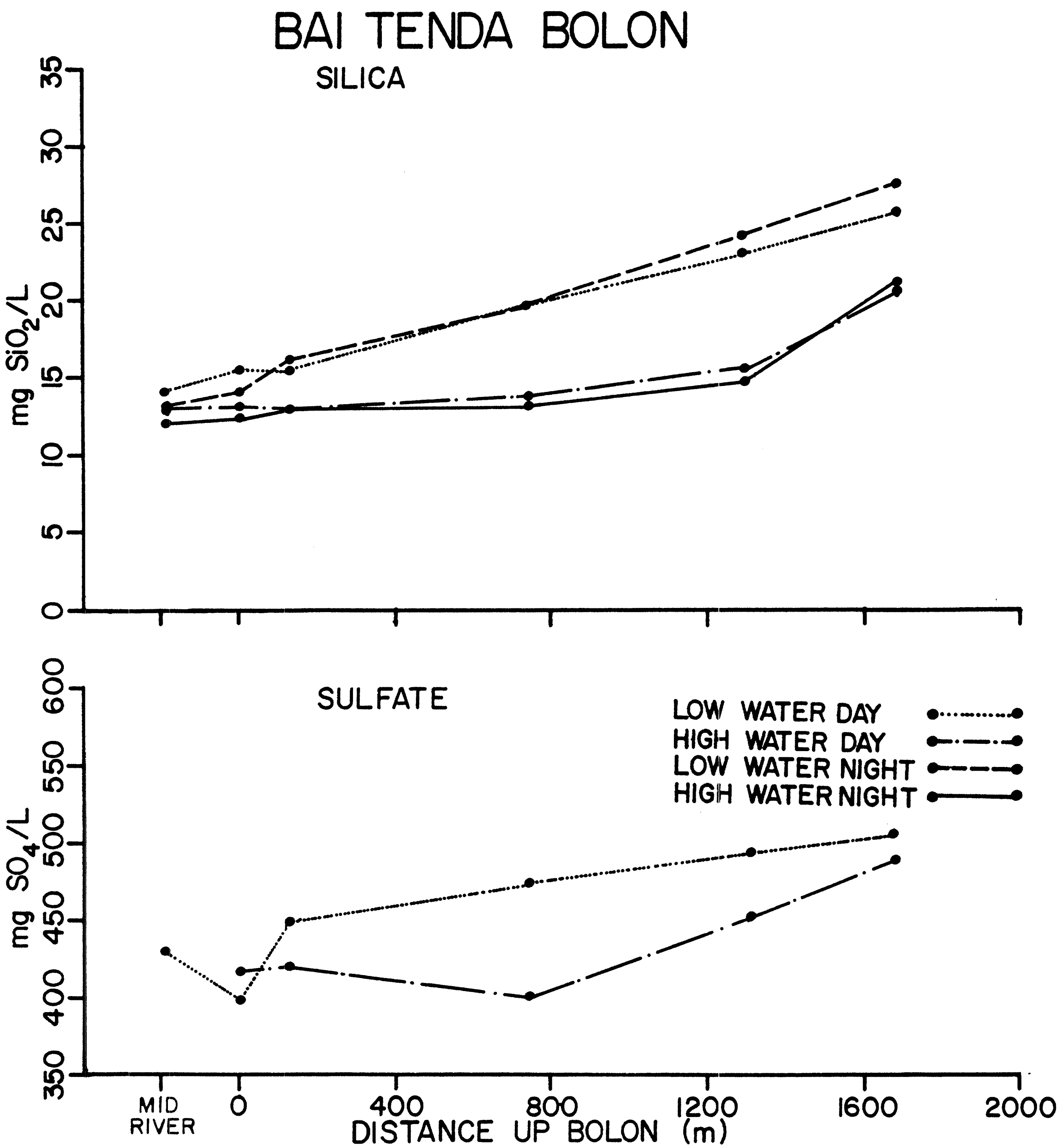

FIGURE 34. Changes in soluble reactive silica and sulfate with distance up Bai Tenda bolon.

bly the result of evaporation on the mud flats. The center of the bolon had the lowest salinities, suggesting that some fresh water seeped into these creeks. The low tide results support this hypothesis, with high salinities observed only at the upstream end of the bolon (Fig. 31). During low tide the low salinity water moved toward the mouth of the bolon. The alkalinity results (Fig. 32) matched the salinity data almost exactly; these results indicate that most of the alkalinity was due to salinity, similar to the main river channel results.

The most consistent and largest change in a physical variable was the drop in pH with distance in the bolon (Fig. 32). Without exception, pH dropped from between 7.6 and 7.5 at the bolon mouth to slightly over 6.9 two km upstream. This decline in pH was evidently due to a change as river water moved onto the mud flats. Comparison of the changes in pH with distance into the bolon for high and low tides indicate the source of the changes. During high tides, pH remained close to mid-river levels over 1 km upstream. In contrast, during low tides when water which had been exposed to the mud flats filled most of the bolon channel, pH levels dropped less than 400 m upstream. The samples collected 2 km into the bolon were not from the end of the creek, rather they were from the point beyond which navigation by a small boat was impossible. It is unknown if pH levels continued to decline farther upstream.

Dissolved oxygen concentrations followed a pattern almost identical to pH (Fig. 32). The lowest percent saturations were consistently observed at 2 km upstream, while the highest levels were at the bolon mouth. Also similar to pH, the change in dissolved oxygen saturation with distance into the bolon varied between high and low tides. The cause behind the difference between high and low tides was assumed to be the same as for pH. Water which had cov-

ered the mud flats at high tide appeared to have a considerable decline in dissolved oxygen. The results are expressed as percent saturation, thus the change is not due to temperature differences alone. Presumably the mud flats have a high level of biological activity due to decomposition of mangrove detritus (Twilley 1985). This high level of decomposition consumes much of the dissolved oxygen in a very short period of time. Without the continual tidal flushing of the mud flats, they would become anaerobic (Twilley 1985). The high level of biological activity also changes many of the chemical characteristics of the bolon water as discussed below.

Chemical Characteristics

The largest changes attributed to the mangrove bolons were in the chemistry of river water as it moved onto the mud flats with the tides. Similar to dissolved oxygen and pH, the chemical characteristics of the water changed with distance into the bolon. Furthermore, those changes differed with the state of the tide and time of day, again similar to dissolved oxygen and pH.

Figure 34 shows the changes in soluble reactive silica and sulfate over distance up Bai Tenda bolon at several different stages of the tide and time of day. For both variables, a moderate increase in concentrations was observed between the bolon mouth and 2 km upstream. The change in soluble silica was dramatic at high tide, with concentrations almost twice as high in the bolon compared to the mouth. At low tide, an increase was still evident, but that increase was smaller than the one at high tide and not apparent at 1.2 km or less upstream. A variety of explanations can be offered for this change in silica. One hypothesis is that ground water seeps into the bolons and this ground water carries higher silica levels than river water. This hypothesis

is compatible with the salinity results which also suggests ground water seepage.

The soluble reactive phosphorus (SRP) results show a consistent decline in concentrations with distance (Fig. 33). On most occasions, SRP concentrations 2 km upstream fell to about half of the bolon mouth levels. The trend was similar among different phases of the tide and time of day. Again, the ground water seepage hypothesis appears a logical explanation because the saline water which enters the bolon from the main river channel has considerably higher SRP concentrations than fresh water farther up the Gambia River. But, SRP is highly affected by biological activity, thus the observed changes cannot be attributed to conservative processes alone.

The largest changes in chemical composition of the water between the main river channel and bolon involved soluble nitrogen. Figure 33 shows a decline in nitrate-nitrogen concentrations that exceeds one order of magnitude. Soluble nitrogen was evidently stripped from the water as it moved into the bolon and onto the mud flats. This trend was consistent for both high and low tides and for day and night. The difference between the bolon mouth and 2 km upstream was larger during low tides; this larger difference was attributed to the fact that the bolon was filled primarily with water that had drained off the mud flats at low tide. The process of removal of nitrate-nitrogen from the water was noted in the samples collected from the main river channel. During ebbing tides, water along the edge of the river was often characterized by very low nitrate-nitrogen concentrations. The changes were not attributed to ground water seepage because ground water was thought to have higher nitrate-nitrogen concentrations than sea water. Twilley (1985) suggested the changes are the result of denitrification. Figure 33 shows the same general

trend with nitrite-nitrogen, although the magnitude of the change was smaller than nitrate-nitrogen.

Particulate Materials

In contrast to the large changes in the chemistry of river water as it moved into and out of the mangrove bolons, suspended solids levels were consistent over time and distance in the bolon (Fig. 31). Gambia River water entering the bolon had different suspended solids levels depending on the state of the tide and time of day. These changes were evident in samples collected from the first few meters into the bolon. Beyond those first few meters, suspended solids concentrations were consistently between 10 and 20 mg/L.

The relatively clear waters of the bolons (low suspended solids loads) supported a rich algal assemblage. The highest chlorophyll concentrations were observed during low tide at 2 km upstream (Fig. 35). Chlorophyll levels in adjoining bolons with fewer overhanging mangrove trees reached 25 μg/L (Healey et al. 1985). High chlorophyll levels in the bolons included high phaeopigment concentrations. In many instances phaeo-fractions exceeded 25% of the total pigment biomass (Fig. 35). The highest phaeo-fractions were observed during the night. An explanation for this pattern was that a large amount of the total plant material in water of the bolon was mangrove detritus. That detritus moved into the water at a relatively constant rate throughout the day and night. In contrast, algal biomass was tied to periods of active photosynthesis during the midday (Healey et al. 1985). Thus at night a greater portion of the total plant material in the bolon water column was leaf litter originating from mangroves.

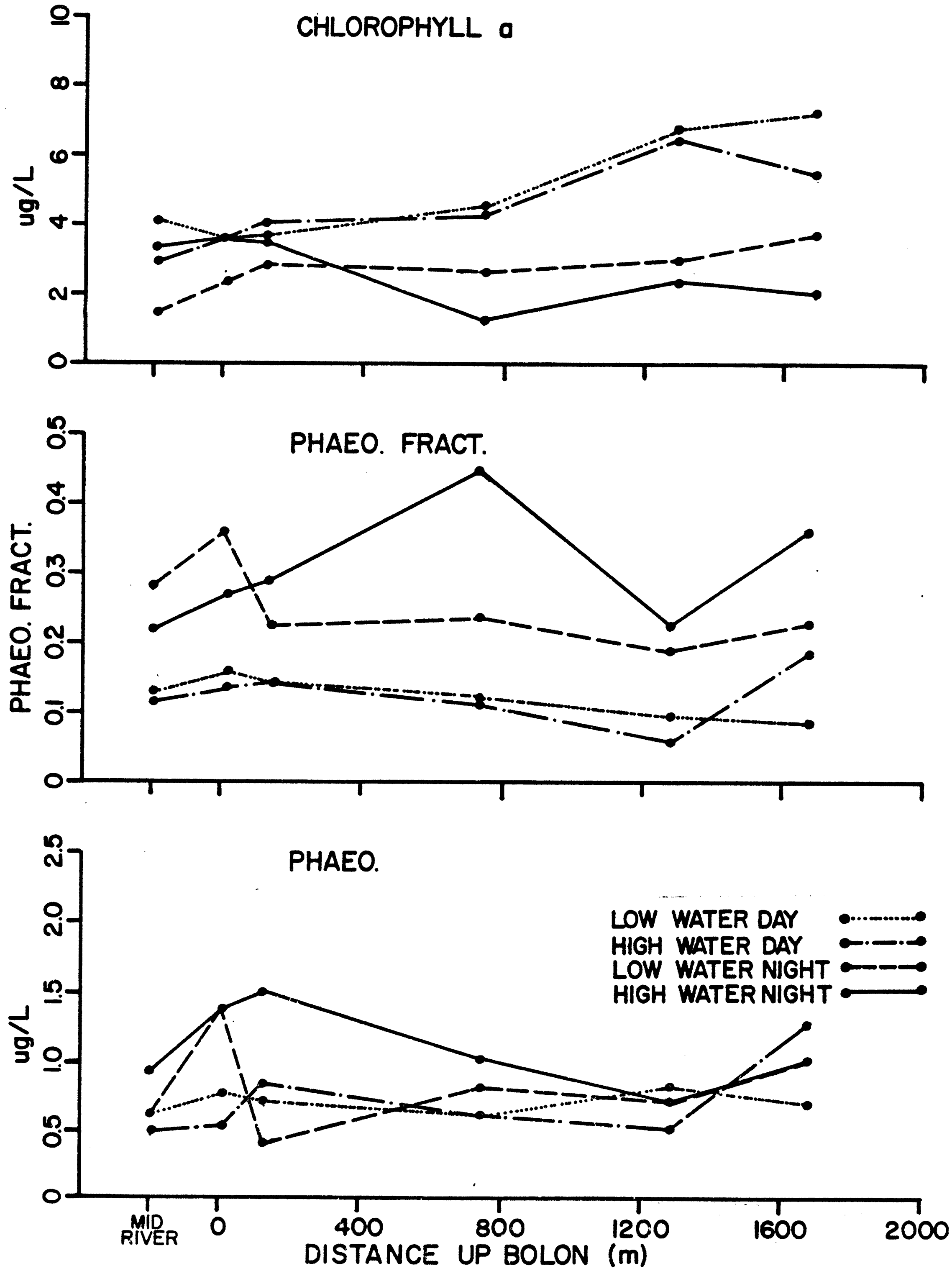

FIGURE 35. Changes in chlorophyll a, phaeo-fraction, and phaeopigment with distance up Bai Tenda bolon.

LOWER RIVER

Physical Characteristics

The lower river zone is defined as that portion of the Gambia River that is subject to tidal influences yet remains fresh water throughout the year. Geographically this is delimited by Kuntaur (250 km upstream from Banjul) and Gouloumbou (510 km upstream from Banjul). Along this section the width of the river averages 100 m to 150 m. Between Gouloumbou and Bansang steep banks define a single meandering channel. Downstream from Bansang to Kuntaur the banks are less steep and the river is braided with large islands (McCarthy, Kai Hai, and Baboon) dividing the channel. Some flood plain areas are present at the downstream limit of the lower river zone. Bansang (310 km upstream from Banjul) was chosen as the primary sampling site for the lower river zone. At that location the river is 180 m wide with an average depth of 8 m. Steep banks create a channel with a nearly rectangular cross sectional profile.

The banks of the river in this zone are lined with dense vegetation composed of tall trees and undergrowth. These trees and shrubs create a greenbelt which contributes a large amount of organic material to the river. The lower half of the lower river zone has numerous bolons, although none support mangroves because of the lack of salt water and/or tidal flushing (Twilley 1985). The upper half of the zone has fewer bolons, in part because the main river channel is lined by tall banks. These banks are not readily cut by small tidal creeks.

Tidal mixing is an important process in the river in this zone despite the absence of salt water all year. Current reversals occur four times per day as the semidiurnal tides propagate upstream of the saltwater-freshwater

interface. Analysis of the physical and chemical results showed that tidal mixing continues to play an important role in the distribution of most variables, similar to the estuarine dynamics. Tidal currents are weaker in the lower river zone than the estuary, with maximum speeds about 0.3 m/s compared to 1.0 m/s respectively.

Aquatic Characteristics

The lower river zone is not affected by the penetration of salt water and as a result has relatively uniform annual chemical and physical characteristics. There are some factors which change throughout the course of the year, these being driven primarily by the annual flood. The most notable was that electrical conductivity decreased from 90 $\mu mho/cm^2$ to 51 $\mu mho/cm^2$ between July and September, and remained at a value between 49 $\mu mho/cm^2$ and 52 $\mu mho/cm^2$ through March (Fig. 36). This cycle appears tied to the influx of low conductivity flood waters in July and August followed by gradual increase in conductivity during the dry season beginning in November or December.

Several other variables displayed decided trends that were also associated with the annual flood. For example, pH increased between July and March from 7.03 to 7.67 (Fig. 36). At the same time that mean pH levels rose during the dry season, the coefficient of variation for pH decreased from 5.1% to 0.5% (Table 15). Dissolved oxygen increased between July and March from 5.90 mg/L (78% saturation) to 7.92 mg/L (97% saturation), while the coefficient of variation fell from 6.7% in July to less than 3% through March (Table 13). Alkalinity decreased between July and September from 36.2 mg/L to 20.2 mg/L and then increased gradually to 24.3 mg/L by March. Variability was highest during flood waters (coefficient of variation 5.4%) and lowest at low waters (coefficient of variation 0.5%) (Table 14). The general pattern was the same

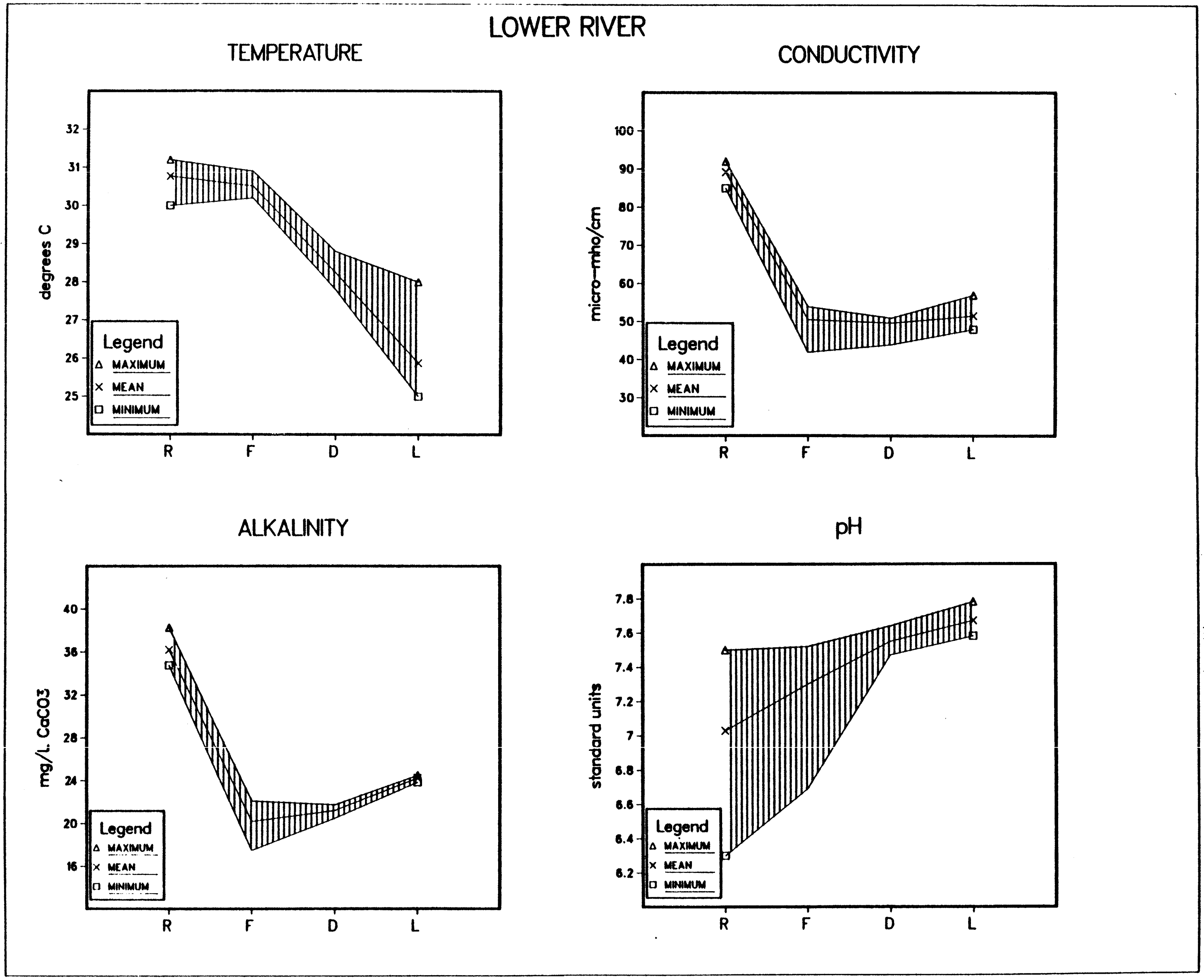

FIGURE 36. Means and ranges of physical and chemical variables for the lower river zone.

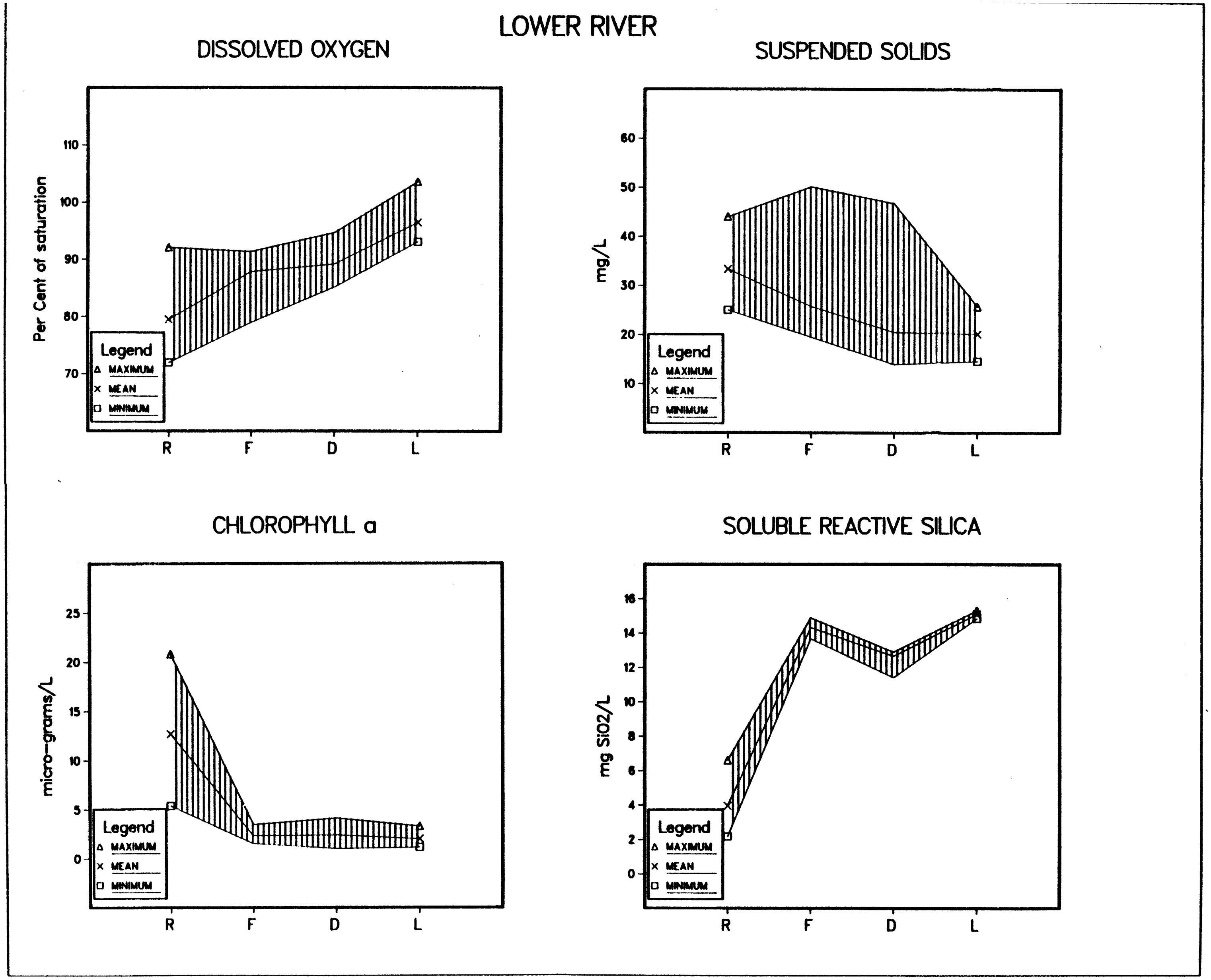

FIGURE 36. (continued).

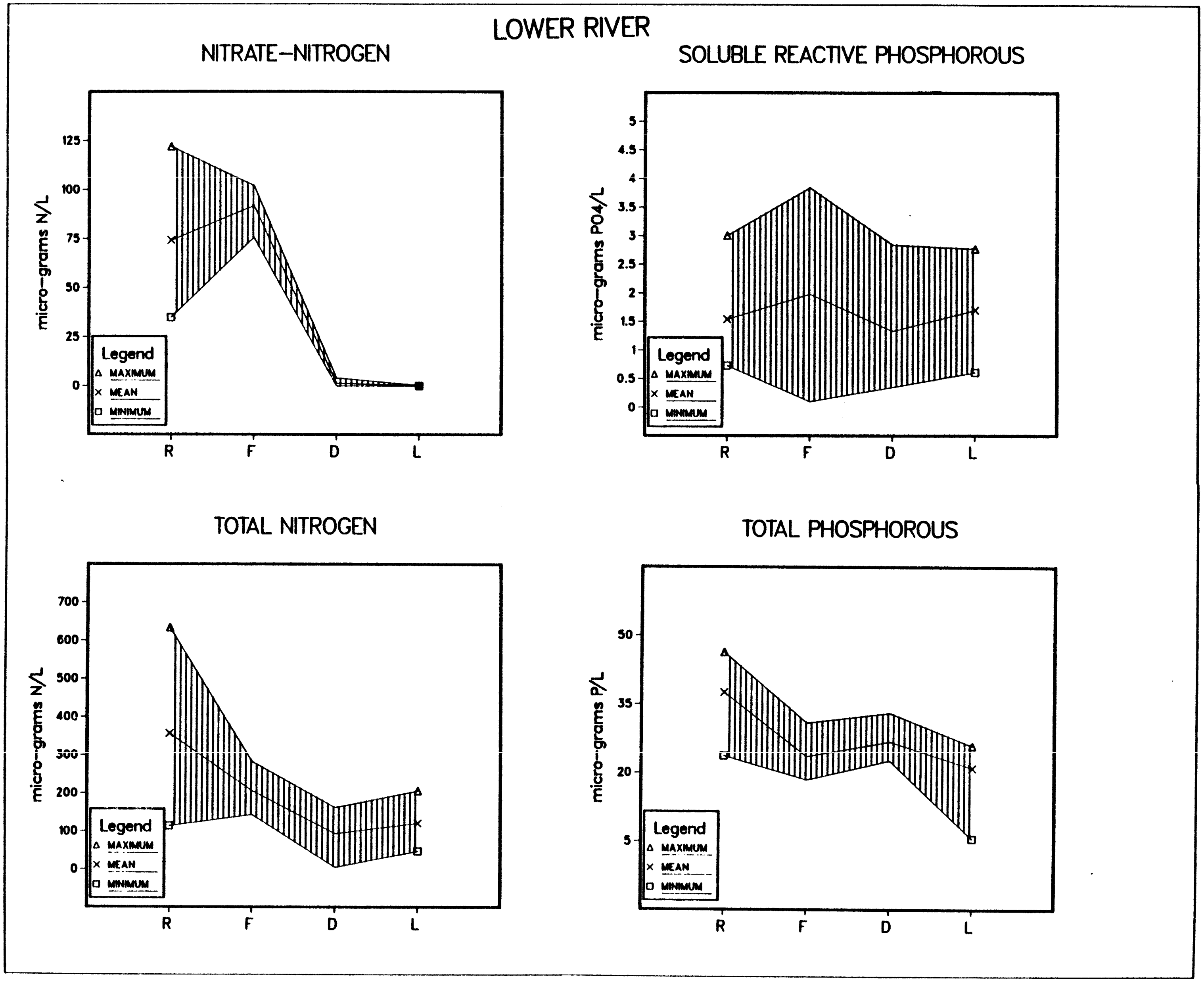

FIGURE 36. (continued).

for all of these variables, a change in the mean concentration between the flood and dry seasons and lower variability during the dry season.

Water temperatures in the lower river zone had the same pattern as in the upper estuary, a trend partially associated with the annual flood and partially with air temperatures (Fig. 36). Water temperatures decreased from 30.8 to 25.9°C between July and March. That decrease was consistent with the annual cycle in air temperatures. Temperatures were more variable during conditions of low flow; the coefficient of variation was less than 1% for the July, September, and December field trips and increased to 2.4% in March.

Chemical Characteristics

The water of the Gambia River in the lower river zone could be described as a very dilute solution with distinct seasonal changes from the annual flood (Lesack et al. 1984). In general, two factors appeared to control the concentration of materials in the water: runoff from the flood and concentration from evaporation. The former dominated the nitrate-nitrogen cycle while the latter appeared to affect the soluble silica cycle.

Soluble silica increased from 3.95 mg/L to 14.3 mg/L between July and September, decreased to 12.7 mg/L by December, and increased to 15.1 mg/L by March (Fig. 36). The coefficient of variation for soluble silica decreased throughout the sampling period (July-March). The greatest decrease occurred between July and September when the coefficient of variation decreased from 38% to 3%. The interaction between the different factors that drive silica concentrations in the Gambia River makes a clear understanding of the annual pattern difficult. But, silica concentrations were generally low in the early part of the flood and increased as streamflow declined. Furthermore,

utilization by algae appeared to alter the concentrations. The correlations between soluble silica and conductivity and chlorophyll were large and negative at -.952 and -.898, respectively. Runoff evidently diluted normal dry season concentrations to a limited extent. Sources of soluble silica probably included ground water seepage from numerous springs in the lower river zone.

The annual cycle of nitrate-nitrogen concentrations was tied directly to the annual flood. A surge of high nitrate-nitrogen water was observed moving down the Gambia River with the onset of the annual flood (Table 8). That surge could be seen in the upper river zone in June (rising water field trip), in the lower river in September (flood water field trip), and in the estuary in December (declining water field trip). In the lower river zone, nitrate-nitrogen concentrations were higher in July and September (74.2 µg/L and 91.9 µg/L, respectively) than December and March (1.38 µg/L and <1 µg/L, respectively) (Fig. 35). The dry season nitrate-nitrogen concentrations were also much less variable than the flood conditions. Nitrate concentrations were not completely in phase with other variables affected by the flood. Nitrate increased and declined during the early portions of the flood as opposed to conductivity which changed more during the latter stages of the flood. The correlation between conductivity and nitrate was only .392.

Trends in soluble reactive phosphorus concentrations in the lower river zone were overwhelmed by the large amount of variation observed on each field trip (Fig. 35). Mean concentrations changed relatively little among the four field trips (Table 10). But, the range of soluble reactive phosphorus values was higher within each field trip than the difference among mean values be-

tween cruises. Furthermore, the coefficient of variation was over 30% for three of the four field trips.

Particulate Materials

Total nitrogen and phosphorus concentrations in the lower river zone of the Gambia River followed the same annual pattern, decreasing between the rising water (July) and low water (March) field trips. Total nitrogen decreased from 356 μg/L to 93.7 μg/L between July and December and increased to 120 μg/L by March (Fig. 36). The coefficient of variation for total nitrogen ranged from 11% to 44% (Table 12). Total phosphorus decreased from 37.6 μg/L to 21.2 μg/L between July and March (Fig. 36). The coefficient of variation ranged from 8% to 19% (Table 11). The probable cause of this annual pattern was the annual flood; flood waters carried higher loads of particulates, which carry nitrogen and phosphorus. The correlation between conductivity and total nitrogen and total phosphorus was .775 and .816, respectively. The calmer waters of the dry season have lower particulate loads, and hence lower total nitrogen and phosphorus concentrations. Suspended solids concentrations followed the same pattern as total nitrogen and phosphorus for the same apparent reason. The flood had much higher suspended solids loads than did the dry season. Suspended solids concentrations decreased between July and March from 33.3 mg/L to 20.2 mg/L (Fig. 36). The coefficient of variation for suspended solids remained between 10% and 20% throughout the sampling period. The range for suspended solids during each field trip was greater than the change in mean values between field trips.

An unusual pattern of chlorophyll concentrations was observed in the lower river zone. An intense algae bloom during the rising waters field trip gave rise to the highest mean concentration for the any one zone (Table 16).

As a result, chlorophyll concentrations were highest in July (12.7 μg/L), decreased by September, and remained at a value between 2.0 μg/L and 2.4 μg/L through March (Fig. 35). The coefficient of variation for chlorophyll was between 15% and 30% throughout the sampling period. The seasonal dynamics of chlorophyll are discussed in considerably more detail in Healey et al. (1985).

Analysis of Variance Inferences

The same Greco-Latin Square experimental design followed in the estuarine zones was also employed in the lower river zone. Use of this design allowed testing of hypotheses concerning the significance of collecting samples at different times and locations in a small region of the lower river zone. Initially the general perception was that a small and narrow segment of the river such as the lower river sampling site should not provide much short-term or small scale variability. But, the results showed that a high degree of variability can be expected, especially over the course of a few days (Tables 26-29).

Fifty six F tests were conducted for each main effect (blocking) variable composed of 14 variables tested over four field trips. The time-of-day/tide main effect yielded 40 significant F tests out of the possible 56 (over 71%). The only variable which did not change significantly with time-of-day/tide over the course of the four field trips was total phosphorus. Out of the fourteen variables tested, significant results ranged from 8 on the low water field trip to 12 on the flood water field trip; the results were relatively uniform among the field trips.

Distinct trends were observed for several variables for time of day and stage of tide. Suspended solids concentrations were higher on ebb tides than flood tides during rising waters and flood waters. During the rising waters

TABLE 26. Summary of Latin Square Analysis of Variance for the rising water season in the lower river zone.

Variable	Transect	Station	Depth	Time/Tide	LF	Miss
Temperature (C)			**	**		0
Conductivity at 25C	*			**		0
Salinity (0/00)						64 na
Dissolved Oxygen (mg/L)	**			**		0
Dissolved Oxygen (% Sat.)	**		*	**		0
Chlorophyll a (μg/L)				**		2
Phaeopigments (μg/L)				**		2
pH				**		0
Alkalinity (mg/L $CaCO_3$)	**			**		0
Suspended Solids (mg/L)		*	**			0
SiO_2 (mg/L)				**		0
PO_4-P (μg/L)						16 na
NO_3-N (μg/L)	*			**		0
NH_3-N (μg/L)						64 na
Total Phosphorus (μg/L)						19 na
Total Nitrogen (μg/L)						18 na

TABLE 27. Summary of Greco-Latin Square Analysis of Variance for the flood season in the lower river zone.

Variable	Transect	Station	Depth	Time/Tide	LF	Miss
Temperature (C)			*	**	**	0
Conductivity at 25C			**	**	**	0
Salinity (0/00)						32 na
Dissolved Oxygen (mg/L)				**		0
Dissolved Oxygen (% Sat.)				**		0
Chlorophyll a (μg/L)				**		0
Phaeopigments (μg/L)				**		0
pH				**		0
Alkalinity (mg/L $CaCO_3$)				**		0
Suspended Solids (mg/L)				**		0
SiO_2 (mg/L)				**		1
PO_4-P (μg/L)						0
NO_3-N (μg/L)				**		0
NH_3-N (μg/L)						8 na
Total Phosphorus (μg/L)						2
Total Nitrogen (μg/L)				**		2

TABLE 28. Summary of Greco-Latin Square Analysis of Variance for the declining water season in the lower river zone.

Variable	Transect	Station	Depth	Time/Tide	LF	Miss
Temperature (C)			**	**	**	0
Conductivity at 25C	**	*	**	**	**	0
Salinity (0/00)						32 na
Dissolved Oxygen (mg/L)	**	**	**	**	**	0
Dissolved Oxygen (% Sat.)	**	**	**	**	**	0
Chlorophyll a (μg/L)				**		0
Phaeopigments (μg/L)						0
pH				**		0
Alkalinity (mg/L $CaCO_3$)				**		0
Suspended Solids (mg/L)					*	0
SiO_2 (mg/L)				**		0
PO_4-P (μg/L)				**		0
NO_3-N (μg/L)		**		**		1
NH_3-N (μg/L)						16 na
Total Phosphorus (μg/L)						0
Total Nitrogen (μg/L)		*				2

TABLE 29. Summary of Greco-Latin Square Analysis of Variance for the dry season in the lower river zone.

Variable	Transect	Station	Depth	Time/Tide	LF	Miss
Temperature (C)			**	**	**	0
Conductivity at 25C	**	*	**	**	**	0
Salinity (0/00)						32 na
Dissolved Oxygen (mg/L)						0
Dissolved Oxygen (% Sat.)						0
Chlorophyll a (μg/L)				**		0
Phaeopigments (μg/L)						0
pH				**	**	0
Alkalinity (mg/L $CaCO_3$)				**		0
Suspended Solids (mg/L)			**	*		1
SiO_2 (mg/L)			**	**		0
PO_4-P (μg/L)				**	**	0
NO_3-N (μg/L)						0
NH_3-N (μg/L)						16 na
Total Phosphorus (μg/L)						3
Total Nitrogen (μg/L)				**		3

period soluble nitrogen concentrations were higher on flood tides than on ebb tides. During the flood, soluble nitrogen concentrations were lower on flood tides than on ebb tides. At declining waters the flood tides had higher soluble nitrogen concentrations than ebb tides, and at low waters the soluble nitrogen concentration was less than the limit of detection for both tides. The magnitude of the difference between the flood and ebb tide concentrations decreased steadily from July to March. Total nitrogen concentrations were higher on flood tides and lower on ebb tides for for the flood and low waters sampling period. Significant tidal effects were observed for soluble silica for all field trips. As with soluble nitrogen, the magnitude of the difference between tides decreased between July and March.

The time-of-day/tide main effect was by far the most important factor affecting the distribution of physical-chemical variables in the lower river zone. The next most important variable was depth of sample, which yielded only 11 out of a possible 56 significant results (about 20%) (Tables 26-29). Those variables which changed significantly with depth were water temperature, alkalinity, conductivity, dissolved oxygen, and suspended solids. Most of these variables were affected to a minor degree by vertical stratification during the dry season when stream flows were low.

The remaining two variables, transect (distance along the river) and station location (distance across the river), had a minor impact on the distribution of variables. Seven of the 56 F tests were significant for transect location and only 2 for station location. Significant impacts from these two blocking variables occurred only during the rising and declining waters field trips with one exception. The only variables affected by transect location were dissolved oxygen, alkalinity, and conductivity. Dissolved oxygen was the

only variable affected by station location. Most of the significant results associated with transect or station location were primarily artifacts of the data analysis and appeared to lack meaningful ecological inference.

While use of the Greco-Latin Square sampling program can have substantial drawbacks due to violation of the statistical model by the database, this was not the case in the lower river zone. Only 10 of the 56 ANOVAs had a significant lack-of-fit F test, indicating that less than 18% of the analyses had significant interaction.

Among all cruises, the analysis suggested that, generally, the effects of transect and station variability were not as important as the effects of depth and the tide-time factors. The depth factor was more important during the dry season when river discharge was low. The tide-time factor was the most important source of variability within each sampling period, but temporal variability decreased between July and March. The interpretation of the time-of-day/tide blocking factor was complicated by the number of sources of variability contained within this one factor. At least three main sources of variability were possible: 1) differences between ebb and flood tides, 2) differences between day and night samples, and 3) differences associated with a change in time, i.e., a water mass moving through the sampling area during the course of the sample collection. Any combination of these effects was possible.

UPPER RIVER

Physical Characteristics

The upper river zone was defined as that portion of the Gambia River which is fresh water but not subject to tidal influences. Further, it is that segment of the river which is generally wide and slow flowing without an

appreciable amount of rapids or streams. Geographically, the upper river zone extends from Gouloumbou, which is 510 km upstream, to the Guinea-Senegal border, which is about 965 km upstream. The upper river zone is the longest segment of the river, extending almost 450 km. Despite the great length of this zone, it is characterized by relatively uniform physical characteristics.

The primary sampling site for the upper river zone was at Kedougou in Senegal Oriental. Kedougou is situated 940 km upstream from Banjul at an elevation of 105 m. This area marks the beginning of the foothills of the Fouta-Djalon mountains where the Gambia River has its source. The catchment basin upstream from Kedougou has a surface area of 7,550 km^2 and is characterized by impermeable soils with a low water retention capacity (HHL 1974). The average slope of the river bed upstream from Kedougou is 4.2 m/km, while at Kedougou the slope is 1.1 m/km. Downstream from Kedougou the the slope of the river bed decreases to .05 m/km at Gouloumbou. At Kedougou steep banks 3 to 5 m in height define the river channel which has an average width of 40 m. The channel widens in some areas and forms a narrow flood plain that contains small shrubs and cultivated fields. During high water these areas are covered by the river. At low water the river does not fill the entire channel and many gravel bars are exposed.

Aquatic Characteristics

The flow regime of the upper river is characterized by two general periods, rainy and dry. During the rainy period (June-October), storms throughout the catchment basin cause pulses of water to pass through the upper river zone. Water levels are high and vary rapidly. Observations during the flood sampling period (29 Sept.) showed that the water level dropped 1 meter over

the course of 12 hours. The remainder of the year (November-May) is dry and water levels are low, averaging 1 to 2 m with very low discharge.

Annual variability in the upper river zone reflected the two-season character of the zone. Water temperatures declined (from 32.2°C to 23.5°C) between June and December and increased (25.5°C) by March (Fig. 37). The range was smaller during the wet season because variable water levels created well-mixed conditions and increased during the low flow period when diel variability was more important. Conductivity and alkalinity followed the same trend except the range was more consistent throughout the year. The lowest conductivity and alkalinity values were found during the end of the rainy season. Seasonal variability in pH was completely masked by diel variability. Dissolved oxygen also displayed a large range in comparison to seasonal differences in the mean.

In general, the characteristics of the water of the upper river zone were tied to rain events in the upper catchment basin. Runoff from the intense thunderstorms had very different characteristics from the ground water that seeps into the river during the dry season. For example, the hardness runoff water was much lower than water found in the river during the rest of the year. Because the catchment basin upstream from Kedougou is composed of hard soils and the river bottom is hard rock in most places, runoff quickly enters the river and moves downstream after a storm. As a result, pulses of water enter the river as runoff and change its aquatic characteristics in only a few hours. As those pulses of water move downstream, conditions begin to return to prestorm conditions until the next pulse of water arrives. An example of these changes was seen in conditions during the rising water field trip (25-27 June). A heavy rainstorm that raised the water level 0.1 m occurred

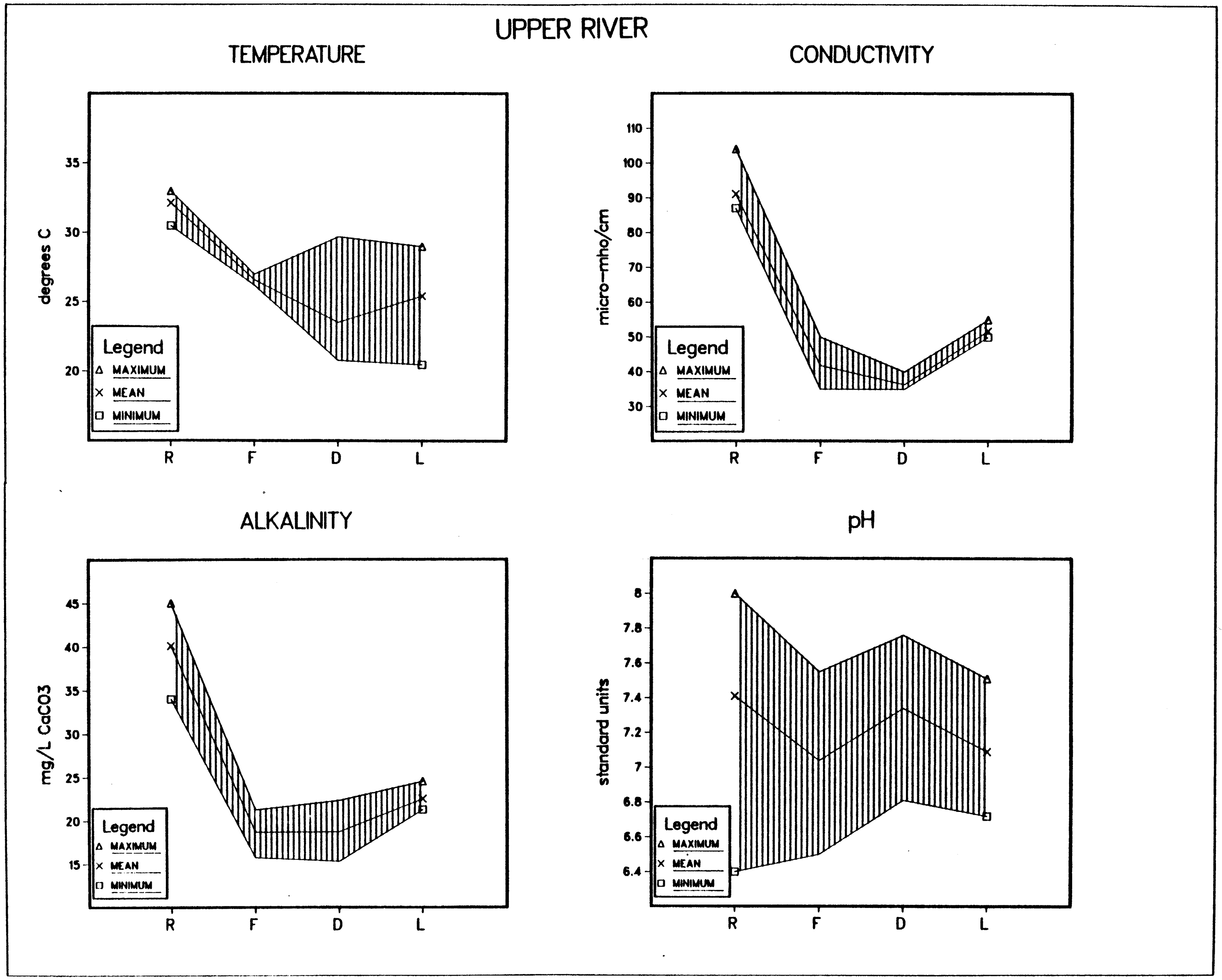

FIGURE 37. Means and ranges of physical and chemical variables for the upper river zone.

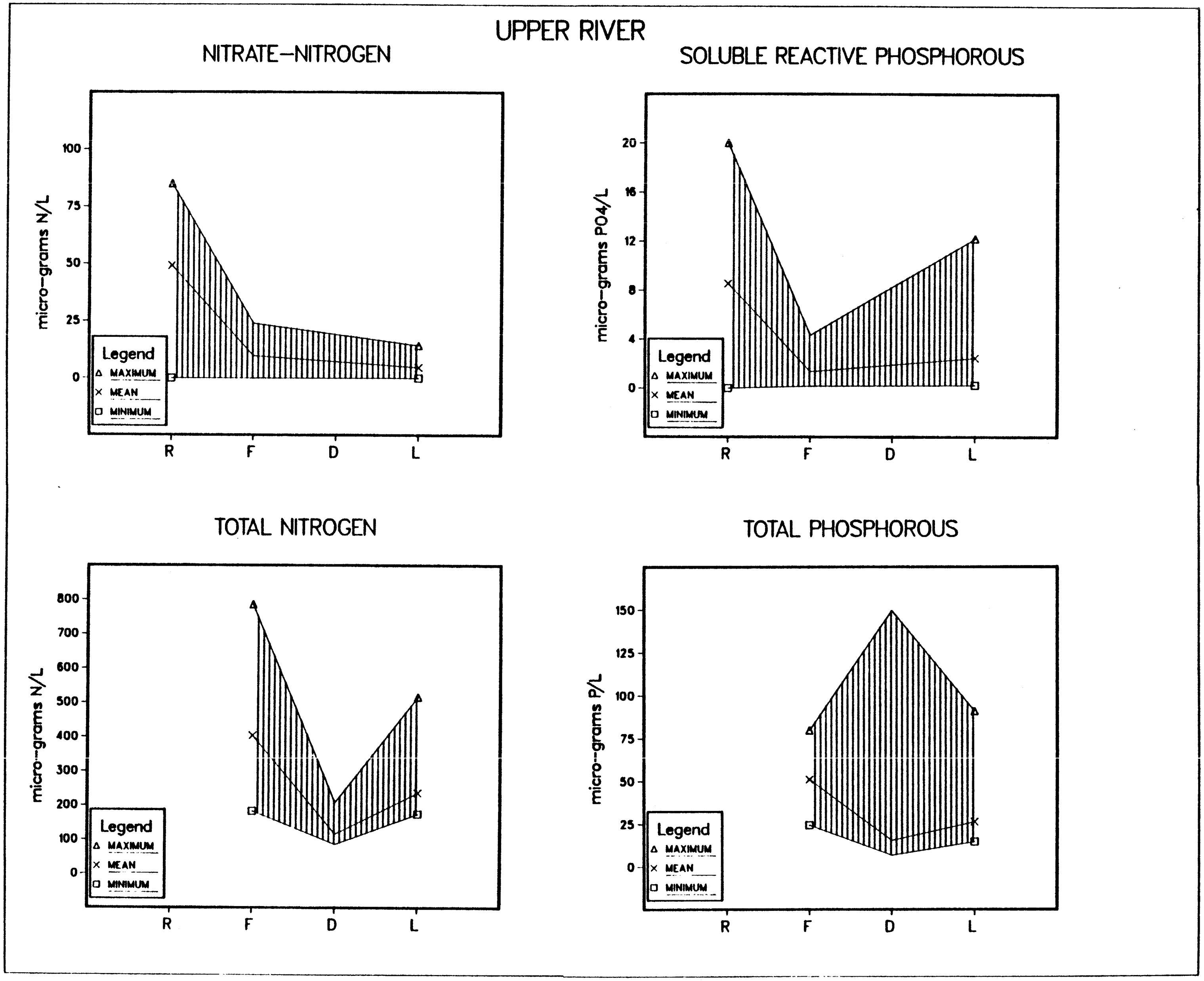

FIGURE 37. (continued).

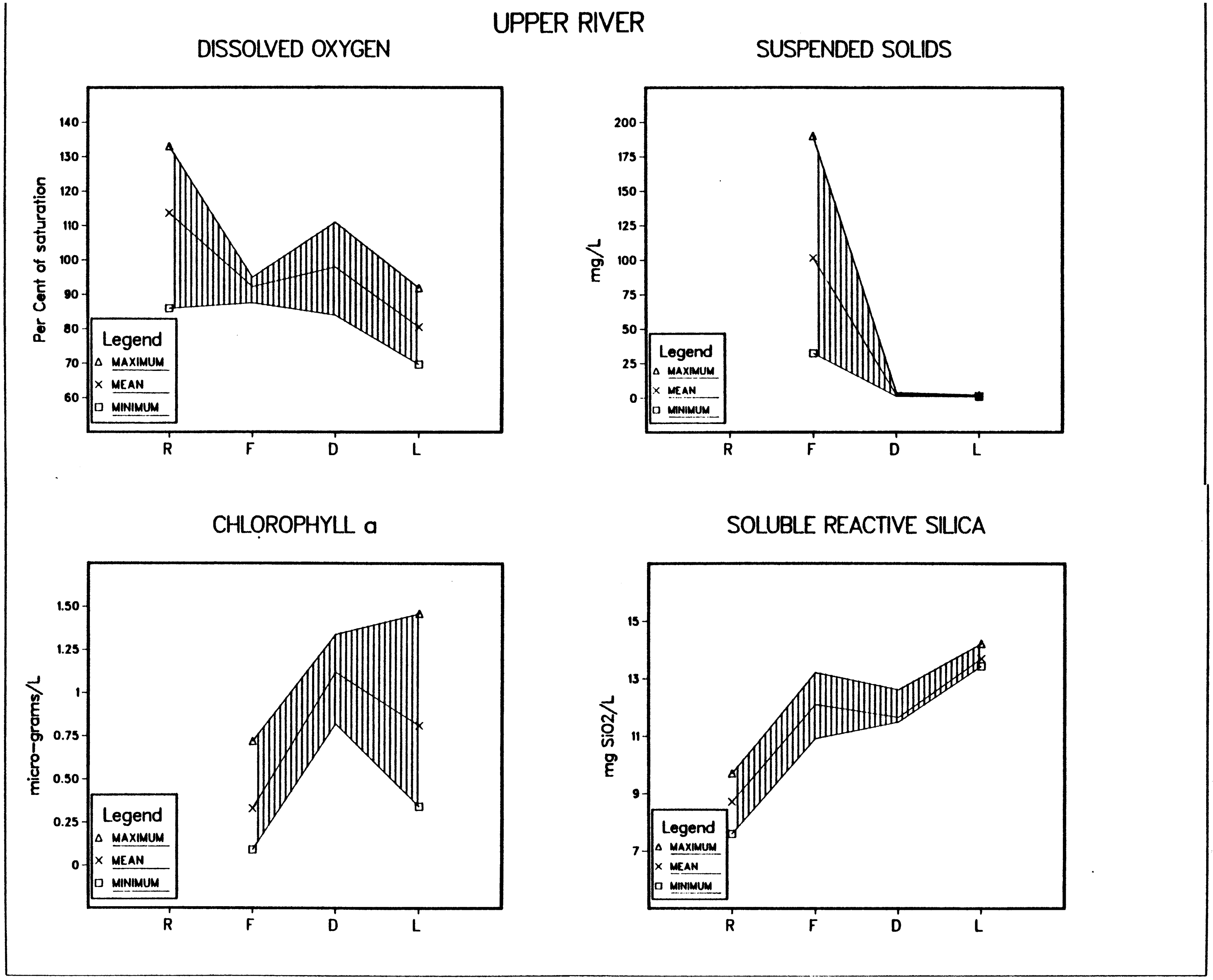

FIGURE 37. (continued).

between the day and dawn samplings. Conductivity, alkalinity, and silica increased over the course of the sampling period while temperature declined (Table 30). The pH dropped from 7.75 to 6.50 after the rain event, but this as well as the change in dissolved oxygen could have been a result of diurnal variability.

Chemical Characteristics

The chemistry of the water in the upper river zone was also dominated by the two seasons. During the dry season, river water had very uniform composition and little temporal variability (Fig. 37). During the rainy season, flash floods caused rapid changes in the chemical nature of the water. Table 31 shows the changes in the mean values of 17 variables over the course of 2 days during the flood season field trip. During this sampling period (29-30 Sept.) water levels were 2 to 3 m higher than the water level observed at the rising waters sampling. Many areas that were dry in June were covered by 1 to 2 m of swift flowing turbulent water. Over the course of the 2-day sampling period water levels dropped almost 1 m, suggesting a major storm had passed through the basin just before sampling began. Differences in mean concentrations for many variables are evident in Table 31. As a result, although annual patterns in many variables were observed, those patterns were usually small in comparison to diel changes during the rainy season.

The most pronounced annual trend was for soluble reactive silica. Ranges of silica concentrations were small during most field trips (Fig. 37). In contrast, among the four field trips, mean silica concentrations increased from over 8 mg SiO_2/L to almost 14 mg SiO_2/L (Table 9). The increase in concentrations appeared directly tied to river discharge. Similar to the lower

TABLE 30. Mean values of physical-chemical parameters collected at Kedougou during the rising water sampling period.

Variable	25 June (day)	26 June (dawn)	26 June dusk)
Temperature (C)	32.5	31.6	31.9
Conductivity	89.1	89.3	101.0
Dissolved oxygen (mg/L)	8.73	6.68	8.10
Dissolved oxygen (% sat)	120.7	90.0	111.3
pH	7.75	6.50	6.95
Alkalinity (mg/L)	40.0	39.3	42.8
Silica (mg/L)	8.2	8.4	9.6
Nitrate (μgN/L)	<LOD	77.8	69.0

TABLE 31. Mean values of physical-chemical parameters collected at Kedougou during the flood water sampling period.

Variable	29 Sept. (day)	29 Sept. (night)	30 Sept. (dawn)	30 Sept. (dusk)
Temperature (C)	26.60	26.50	26.25	27.00
Conductivity	35.5	48.0	40.3	36.0
Dissolved oxygen (mg/L)	7.62	7.41	7.44	7.12
Dissolved oxygen (% sat)	94.8	92.3	93.3	88.9
Chlorophyll a (μg/L)	0.54	0.30	0.27	0.21
Phaeopigments (μg/L)	0.97	0.76	0.51	0.49
Phaeo-fraction (%)	64.	72.	65.	70.
pH	6.91	6.96	7.33	6.94
Alkalinity (mg/L)	18.1	17.0	19.9	19.8
Suspended solids (mg/L)	143.9	171.8	52.2	38.5
Silica (mg/L)	11.1	11.5	13.2	12.6
Phosphate (μgN/L)	1.2	2.0	1.2	1.1
Nitrate (μgN/L)	12.0	9.0	1.6	7.9
Total phosphorous (μgP/L)	66.4	72.1	35.3	30.8
Organic phosphorous (μgP/L)	65.2	70.1	34.1	29.7
Total nitrogen (μgN/L)	534.	551.	262.	267.
Organic nitrogen (μgN/L)	522.	542.	260.	259.

river zone, low silica runoff was replaced by higher silica ground water during the dry season.

Soluble nitrate-nitrogen concentrations followed a pattern that was observed throughout the length of the Gambia River. Runoff was high in nitrate-nitrogen and could be traced as as pulse of water moving down the river with the annual flood. The runoff from early in the rainy season (April-June) appeared particularly enriched in nitrate. The results from the upper river zone matched this pattern. The highest nitrate-nitrogen concentrations were found during the first (rising waters) field trip (Fig. 37). Nitrate concentrations fell during each succeeding field trip until they reached their observed annual low during the March field trip (low water). The coefficient of variation for nitrate-nitrogen dropped from over 37% during the first field trip to under 3% by March (Table 8).

Mean soluble reactive phosphorus (SRP) concentrations followed the same pattern as nitrate-nitrogen, decreasing from the highest values to the lowest levels from June to March respectively (Fig. 37). The mechanisms behind this pattern were probably the same as with nitrogen. Runoff was initially high in soluble phosphorus and dry season river water had low phosphorus concentrations. The major difference between the two variables is that within-field-trip variability was extremely high for SRP compared to nitrate-nitrogen. The lowest coefficient of variation for SRP was over 53% and usually approached 95% (Table 10). These results suggest that seasonal trends in SRP were small compared to short-term temporal changes.

Particulate Materials

The two-season nature of the Gambia River in this zone was very evident in the particulate materials. Flood waters primarily originated as runoff and

as a result carried large amounts of debris and associated particulates into the river from the upper catchment basin. As mentioned above, during the flood sampling period (29-30 Sept.) water levels were 2 to 3 m higher than on the previous field trip. These high waters were turbid (Secchi depth of 5 cm) with a large quantity of debris. Thunderstorms in the vicinity of the sampling site evidently caused the change in water levels and concomitant change in many of the variables measured. The change was greatest for variables associated with particulates (e.g., the value of suspended solids decreased 70% in 12 hours between the night and dawn sampling periods) (Table 31). Both chlorophyll a and phaeopigments decreased by 50% over the span of the entire sampling period.

Suspended solids appeared to be closely linked to the flow regime of the river. During the flood period the mean value for suspended solids was 101 mg/L and during the period of low discharge the mean values for suspended solids were 2.4 mg/L and 1.3 mg/L for the declining waters and low waters periods, respectively (Table 7). Inferences pertaining to the seasonal variability of the remaining parameters (chlorophyll, total phosphorus, and total nitrogen) were difficult to make due to the high variability of these parameters within sampling periods and among only three field trips. Generally, total nitrogen and phosphorus concentrations were highest during the flood and declined into the dry season (Fig. 36). Chlorophyll behaved in an opposite seasonal trend, although overall chlorophyll concentrations were very low in this zone.

Analysis of Variance

The results of the Greco-Latin Square analysis showed that the time factor was the only blocking factor that had a significant effect for any of the

variables (Tables 32-34). These results suggested that during all sampling periods the river was well mixed and that small spatial differences (e.g., from one side of the river to the other) were not important in relation to variability with time.

The ANOVA summary for the time blocking factor for all variables and field trips indicated that the sampling periods could be divided into two groups (Table 35). For the flood water sampling period, which was characterized by rapidly changing water levels, all variables except soluble nutrients (soluble silica, nitrate-nitrogen, and soluble reactive phosphorus) had significant differences. During the declining waters and low waters sampling periods, the variables that had significant differences were temperature, conductivity, pH, and dissolved oxygen. The mean values of these parameters for the time periods sampled suggested diel variability as a possible explanation (Table 36). Temperature was highest during the day when maximum solar heating occurred and lowest at dawn after a night of cooling. During the daylight hours photosynthesis may have increased the concentration of dissolved oxygen, while at night respiration probably lowered dissolved oxygen concentrations. Lower values for pH were observed at dawn, and were often associated with an increase in dissolved carbon dioxide (Wetzel 1983). Diel variation was observed during the rising waters and flood sampling periods but was somewhat obscured by the large variability due to high water "pulses" present at those times.

HEADWATERS

Physical Characteristics

The headwaters region of the Gambia River was considered the segment of the river from the source near Labé in Guinea to the escarpment just upstream

TABLE 32. Summary of Greco-Latin Square Analysis of Variance for the rising water season in the upper river zone.

Variable	Transect	Station	Depth	Time/Tide	LF	Miss
Temperature (C)						16 na
Conductivity at 25C						16 na
Dissolved Oxygen (mg/L)						16 na
Dissolved Oxygen (% Sat.)						16 na
Chlorophyll a (μg/L)				**		0
Phaeopigments (μg/L)				**		0
pH				**		2
Alkalinity (mg/L $CaCO_3$)				**		2
Suspended Solids (mg/L)		*		**	*	0
SiO_2 (mg/L)	*	*		**		0
PO_4-P (μg/L)						0
NO_3-N (μg/L)					**	0
NH_3-N (μg/L)						0
Total Phosphorus (μg/L)				**		0
Total Nitrogen (μg/L)				**		0

TABLE 33. Summary of Greco-Latin Square Analysis of Variance for the flood season in the upper river zone.

Variable	Transect	Station	Depth	Time/Tide	LF	Miss
Temperature (C)				**		0
Conductivity at 25C	*			**	**	0
Dissolved Oxygen (mg/L)				**		0
Dissolved Oxygen (% Sat.)				**		0
Chlorophyll a (μg/L)						0
Phaeopigments (μg/L)				*	*	0
pH				**		0
Alkalinity (mg/L $CaCO_3$)				*		0
Suspended Solids (mg/L)						1
SiO_2 (mg/L)						0
PO_4-P (μg/L)						32 na
NO_3-N (μg/L)						32 na
NH_3-N (μg/L)						32 na
Total Phosphorus (μg/L)						0
Total Nitrogen (μg/L)	*					0

TABLE 34. Summary of Greco-Latin Square Analysis of Variance for the declining water season in the upper river zone.

Variable	Transect	Station	Depth	Time/Tide	LF	Miss
Temperature (C)						4 na
Conductivity at 25C						4 na
Dissolved Oxygen (mg/L)						16 na
Dissolved Oxygen (% Sat.)						16 na
Chlorophyll a (μg/L)						12 na
Phaeopigments (μg/L)						12 na
pH						16 na
Alkalinity (mg/L $CaCO_3$)						16 na
Suspended Solids (mg/L)						1
SiO_2 (mg/L)					**	0
PO_4-P (μg/L)						0
NO_3-N (μg/L)				*	*	0
NH_3-N (μg/L)						0
Total Phosphorus (μg/L)						12 na
Total Nitrogen (μg/L)						12 na

TABLE 35. ANOVA summary of the time factor for the upper river zone.

Variable	Rising	Flood	Declining	Low
Temperature	**	**	**	**
Dissolved oxygen (mg/L)	**	**	**	**
Dissolved oxygen (% sat)	**	**	**	**
pH	**	**	**	**
Conductivity	**	**		
Alkalinity	**	**		
Suspended solids	--	**		
Chlorophyll a	--	**		
Phaeopigments	--	**		
Total phosphorous	--	**		
Total nitrogen	--	**		
Silica	**	**		
Nitrate-nitrite	--	--		
Phosphate	--	--		

** significant ($p<.01$)
-- no analysis

TABLE 36. Diel variation in mean values of temperature, pH, and dissolved oxygen at the upper river sampling site for all field trips.

	Rising	Flood	Declining	Low
		Temperature		
Dawn	31.6	26.3	22.4	25.1
Day	32.5	26.6	29.2	28.3
Dusk	31.9	27.0	21.1	25.0
Night	--	26.5	21.7	21.1
		pH		
Dawn	6.50	7.33	7.07	6.78
Day	7.75	6.91	7.59	7.12
Dusk	6.95	6.94	7.41	7.34
Night	--	6.96	7.29	7.13
		Dissolved Oxygen (mg/L)		
Dawn	6.66	7.44	7.89	6.11
Day	8.73	7.62	8.37	6.68
Dusk	8.10	7.12	8.69	7.46
Night	--	7.41	8.41	7.12
		Dissolved Oxygen (% sat.)		
Dawn	90	93	91	72
Day	121	95	108	83
Dusk	111	89	97	88
Night	--	92	96	79

from the Guinea-Senegal border. This region is characterized by numerous small streams and rivers running through generally hilly and mountainous terrain. The average slope of the river bed in this region is over four times that of the upper river zone. The river primarily runs through deep gorges with tall (up to 20 m) steep banks in many locations. The numerous floods have scoured the river down to rock in most places. The hard rock bottom is composed of slate as are the lower several meters of the river banks. Rock outcroppings are common and result in rapids when the river is flowing. Most of the headwaters region is covered by vegetation, although this cover can become extremely thin during the late dry season.

Numerous deep pools are found in the headwaters between the rapids. These pools vary in size from only a few meters in length to over 1 km. The pools play a significant role in the ecology of the river in that they serve as refuge for many aquatic organisms during the dry season. Some of these pools are over 4 m deep throughout the dry season.

The primary sampling location for the headwaters region was on a branch of the Gambia River approximately 5 km from Balaki and slightly over 1,000 km upstream from Banjul. The Gambi River in this location is approximately 65 m wide. The river banks are about 15 m high and composed of slate and consolidated soils; the lower 1-2 m of the banks are slate scoured by numerous floods. The river bottom is slate, composed of slabs with a step-like appearance oriented downstream. Increasing and decreasing "steps" of slate on the bottom provide sufficient relief to create numerous small pools up to 3 m deep during the dry season. At this location, the Gambia River is about equal portion rapids (less than 1 m deep or dry during most of the year) and deep

pools. Similar to the other freshwater river zones, dense vegetation overhangs much of the river from the banks.

Aquatic and Chemical Characteristics

Three field trips were conducted to the headwaters region during the declining, low, and rising waters seasons in December 1983, and March and June 1984, respectively. The character of the Gambia River in the headwaters region is very similar to the upper river. The dominant aquatic characteristic of this region is the presence of the wet and dry seasons. The contrast between the two seasons is greatest in the headwaters zone because the river changes from a non-flowing to a rapidly flowing system. That change is not a smooth transition because the early season rains (up to the first half of the rainy season) cause the river to temporarily flow for a few days, after which it recedes to non-flowing conditions again. As the rainy season advances, the flow in the river becomes more regular until the annual flood develops. Highest discharges are found at the end of the rainy season in October or November. The thermal cycle of the river follows air temperatures very closely. The warmest water temperatures were observed in the spring before the beginning of the rainy season (Table 37).

The chemistry of river water in the headwaters zone was characterized by extremely low concentrations of almost all dissolved substances (Table 37). Much of the water in the Gambia River comes from runoff or shallow ground water aquifers (Harza 1985). The soils of the region are hard and impermeable, giving rise to rapid runoff from the intense storms of the rainy season. Over 25% of the rainfall quickly enters the river, compared to less than 10% in the lower portion of the basin. This form of runoff does not contribute substantial amounts of dissolved or suspended solids to the river. As a re-

TABLE 37. Means of selected physical and chemical variables from the headwaters region of the Gambia River, 1983-84.

Variable	Declining Waters	Low Waters	Rising Waters
Temperature (°C)	21.8	30.7	24.0
Conductivity (μm/cm)	30.0	94.8	45.0
Dissolved oxygen (mg/L)	6.86	5.96	3.74
Dissolved oxygen (% sat.)	78.7	80.3	43.3
pH	7.37	7.46	7.60
Alkalinity (mg/L)	16.9	47.4	22.8
Soluble silica (mg/L)	10.8	6.58	ND*
Soluble phosphorus (μg/L)	13.4	3.50	ND*
Nitrate-nitrogen	.013	.01	LD+

* - No data
\+ - Limit of detection

sult, total dissolved solids are very low. The conductivity levels in the river were low all year, but reached their annual minima during the rainy season (Table 37). Likewise, alkalinities were generally low, with the nadir during the declining water field trip (December). The pH and alkalinity results indicated very soft water with minimal buffering capacity. Dissolved oxygen concentrations were generally high, with average percent saturation never falling below 40% and usually close to 80%. Overall, water quality in this segment of the Gambia River was very good.

Soluble nutrient conditions indicated a very nitrogen poor environment which in turn appeared to limit overall aquatic productivity (Healey et al. 1985). Only two sets of nutrient samples were analyzed from this segment of the river. Both sets indicated that soluble silica and soluble reactive phosphorus were at high concentrations during the rainy and dry seasons. Soluble nitrate-nitrogen concentrations, in contrast, were extremely low and below the limit of analytical detection. Although the chemical techniques used in the headwaters were not as accurate as for the other samples, algal bioassays con-

firmed the low levels of nitrate-nitrogen in the river. Primary productivity estimated by ^{14}C uptake was minimal despite relatively clear water (Healey et al. 1985). Secchi disk readings exceeded 2 m in many places in the headwaters zone.

SUMMARY

The Gambia River and associated tributaries form a diverse aquatic system ranging from small streams in the headlands to an extensive estuarine complex. This diversity, a variety of physical and chemical environments, generates an overall richness of character for the river. Geographically the Gambia River has two main segments, the estuary and the freshwater river. The former is composed of two types, with very saline water in the lower estuary and brackish water in the upper estuary. The lower estuary takes on many of the characteristics of the adjoining coastal environment with typical marine chemistry and biota. The upper estuary is brackish all year and as a result is inhabited by those organisms which can tolerate a large range of salinities. The freshwater segment of the Gambia River is composed of three distinct zones: the lower river with diurnal tides; the upper river which lacks tides and is composed of pools and rapids; and the headwaters located among the Fouta Djalon Mountains of Guinea. The headwaters zone differs from the upper river zone primarily by the size of the river, the dendritic nature of its drainage basin, and its highly seasonal discharge pattern. While the boundary between these zones is somewhat arbitrary, a distinct physical and chemical environment was identified with each zone.

Hydrology is the main factor controlling the ecology of the Gambia River, and exerts its influence in two ways. First, the annual flood is the single most important seasonal process in the river basin. The waters of the freshwater river zones remain relatively constant in their chemical and physical characteristics throughout the dry season, which usually runs from December to April, but the onset of the annual flood brings rapid and major changes. The second hydrological influence is tides, the dominant physical

force in the estuarine zones. Tidal waves provide the energy which mixes the river and allows the intrusion of salt water as far as 250 km upstream. Tidal mixing is a dominant factor in moving water into and out of the numerous small creeks in the lower half of the river. The lower freshwater and upper estuary zones are affected both by the annual flood and tidal mixing.

The pattern of rainfall in the Gambia River Basin is highly seasonal. The annual rains in the headwaters zone begin in March and continue until November or December. Farther downstream the rains begin later and end earlier in the year. The annual flood begins a few months after the rainy season starts, usually in June or July, and continues until December. Annual rainfall varies considerably from year to year and throughout the basin. Highest rainfall levels exceed 1,700 mm/yr in the headwaters zone and lowest levels are less than 600 mm/yr in the northeast portion of the basin.

Tidal dynamics within the river are complex. The generally flat terrain of the lower half of the basin allows the penetration of tidal waves as far as 510 km upstream, approximately one half the length of the river. Tidal ranges are large, with spring tides approaching 2 m at the river mouth. Ranges decrease more or less uniformly with distance to less than 10 cm at 500 km upstream. Because tidal waves penetrate over 500 km into the Gambia River, five tides are found in the river at one time. This results in two high and three low or two high and three low tides in the river at once.

The movement of tides deep into the Gambia River carries salt water up to 250 km inland during the end of the dry season. The onset of the annual flood provides a large mass of fresh water which pushes the salt water back toward the ocean. As a result, the chemistry of the upper estuary zone has a distinct annual cycle controlled by the movement of salt water into the river.

This annual cycle creates an environment which changes from relatively brackish (13 ppt salinity) to fresh and back to brackish water within 1 year.

The chemistry of Gambia River water is directly under the influence of the two dominant physical forces, the annual flood and tidal mixing. In the lower estuary zone and portions of the upper estuary zone, tidal mixing and salt water intrusion create conditions similar to the coastal ocean. These conditions include a period of cool (23°C) and highly saline (34 ppt) water during the dry season and warm and slightly less saline water during the wet season. In this zone, highly buffered sea water (pH 7.9) is present throughout the year. In comparison to fresh water, the lower estuary has low dissolved silica (average annual concentration 1.4 μg/L) and very high soluble reactive phosphorus (average annual concentration 22.2 μg/L). The only chemical variable which showed a distinct seasonal trend in this zone was nitrate, which increased from 7.7 to over 54 μg/L between the early and late stages of the annual flood.

The upper estuary zone is a transition area between the highly saline lower estuary and freshwater segments of the river. This zone has large shifts in chemistry during the course of one year. During the dry season (December through May) the waters of the upper estuary are saline (about 13 ppt) and relatively cool (23.5°C). The rainy season brings warm, fresh water into this zone. This shift from saline to fresh water and back each year changes the chemistry of the water from highly buffered to relatively unbuffered. The average pH shifts from 7.4 in the dry season to 7.0 during the flood season. Likewise, the chemical variables change from the low silica and high phosphorus conditions of salt water to the opposite during the flood. Silica concentrations increase from below 9 to over 15 mg/L and phosphorus

shifts from 8.5 to 4.6 µg/L. Nitrate-nitrate concentrations were elevated in the upper estuary compared to the other zones of the Gambia River; average concentrations ranged from 43 to 218 µg/L.

Studies of the bolons showed substantial changes in the chemistry of the water moving onto the floor of the mangrove forests. These changes were attributed to intense biological processes and the seepage of fresh water into the upstream end of the bolons. The major changes in water chemistry as water moved from the river into the bolons over the course of one tidal cycle were: a decline in water temperature, suspended solids, pH, dissolved oxygen, nitrate-nitrogen, and soluble reactive phosphorus and an increase in soluble silica and sulfate concentrations. The largest changes were the decreases in pH and nitrate-nitrogen. These two declines were attributed to denitrification which occurred on the mud flats of the mangrove floor.

The lower river zone has two factors affecting the chemistry of the river. Tidal waves kept the water column well mixed although distinct changes in water chemistry were observed with the changing tide. Very large changes in the chemistry were associated with the annual flood. The largest change was the influx of high nitrate-nitrogen concentrations with the onset of the flood. Nitrate concentrations increased from below 1 µg/L to over 28 µg/L between the end of the dry season and onset of the wet season. Soluble reactive silica also displayed a distinct annual trend, with low concentrations during the early wet season followed by more uniform values for the remainder of the year. The only other variable to undergo large annual changes was conductivity, which decreased from over 89 to less than 50 µmho/cm during the flood.

The upper river and headwaters zones were characterized by two very different chemical regimes. During the dry season, conditions in the river were

extremely stable primarily because of the low net discharge of the river. With the onset of the annual flood, runoff entering the river quickly shifted the chemistry of the water. Runoff was relatively high in all soluble nutrients, especially nitrate-nitrogen. As a result, in the upper river zone, nitrate concentrations increased from below the limit of detection to over 49 μg/L in a very short time. Conductivity of flood water was low compared to the dry season; the average conductivity fell from over 91 to 36 μmho/cm between the dry season and flood seasons. The thermal cycle of the river was closely related to air temperatures. The highest temperatures (average 32.3°C) were observed just before the onset of the rainy season. The lowest temperatures (23.5°C) were found during the middle of the dry season.

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